Full Scale Tests on the Discharge Characteristics, Drainage Characteristics and Fire Suppression Performance of Portable Compressed Air Foam System

By

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A thesis submitted to The Faculty of Graduate and Postdoctoral Affairs In partial fulfillment of the requirements for the degree of

Master of Applied Science

In

Civil Engineering

Department of Civil and Environmental Engineering

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ABSTRACT

Existing portable foam extinguishers generate fire-fighting foam at high pressures with the aid of air aspirating nozzles. These systems could encounter several limitations at the point of application such as poor foam quality and insufficient momentum to reach the seat of the fire. Research had shown that by incorporating compressed air into the portable foam system, the integrated foam system could generate superior quality foam with high momentum when properly installed with the right components.

This research investigated the discharge characteristics, drainage characteristics and fire suppression performance of a portable compressed air foam system. The study also investigated compliance with the requirements of NFPA 10 and CAN/ULC-S508 for a new portable system. Full scale tests were conducted to ascertain the results under various operating conditions.

The effect of hose length on the expansion ratio of the foam was investigated with a range of parameters such as varied foam concentrate, hose lengths of 1-m to 3-m and pressure in the ranges of 2.42 bar and 5.52 bar. The foams were partially developed inside the 1- hose leading to increase in expansion ratio as the pressure increases whereas the same solutions for both 2-m and 3-m hose lengths generated fully developed foams inside the hoselines.

Discharge range tests were conducted to investigate the horizontal projection of the foam. The test results showed longer projection at higher momentum in the 2-m and 3-m hose as compared to the 1-m hose. Likewise, the portable system could generate uniform and consistent foam at low pressures when the foam is fully developed inside the hose before discharge.

The test results on flow rate showed that when the portable system is operated at a low rate, its application time increases thereby generating more foam for fire suppression and heat exposure

protection without altering the consistency of the foam. Overall, all the tested foams met the requirements of the CAN/ULC-S508 standard.

The drainage rate of foams with no imposed heat depends on the foam expansion ratio. The test results for the free drainage of foams showed higher drainage rate in foams with low expansion ratio in contrast to the foams subjected to thermal radiation. However, all the tested foams exhibited a similar drainage pattern, in terms of foam mass loss, at different drainage rates.

Foams exposed to thermal radiation showed similar temperature profiles but disintegrated at different drainage rates. A high drainage rate was observed in foams with higher expansion ratio at the same or higher irradiance levels. Similarly, the percentage of evaporated foam and mass loss rate was greater in foams with higher expansion ratio when exposed to the same or higher irradiance levels. However, the time to half mass loss decreased with increase in foam expansion ratio and heat flux.

Test conducted to determine the extinguishment ability of a portable CAF system with a 2-L capacity demonstrated that the system could extinguish 0.23 m^2 fire and 0.46 m^2 gasoline pool fires. Likewise, the system was effective in extinguishing 8 layers wood crib fires but could only control the burning of 12 layers wood crib fires without total extinguishment. However, this could be achieved in an enclosed space with no interference of wind.

ACKNOWLEDGEMENT

My gratitude goes to the Creator of the universe for His divine favor, exceeding grace and overflowing blessings I was privileged to enjoy during my Master's study. All glory, honor and adoration be unto The All Sufficient God.

The successful completion of this program would not have been possible without the unparalleled support, motivation and guidance of my supervisor, Prof George Hadjisophocleous. I am grateful for his mentorship in the profession and the opportunity given to me to contribute to the advancement of fire safety engineering.

My profound gratitude goes to Terry Brennan, the Division Chief of Training Ottawa Fire Services, the Fire Chief of the Ottawa Fire Service Training Centre for allowing me to use their facility to conduct the experiments. My gratitude also goes to Dr. Paul Lhotsky and Ba Lam-Thien for their support and assistance during the research.

To my friends; Anjolaoluwa Lasisi, Mariam Bulus, Aba Owusu, Rheanna Johnson, David Agboola, Boluwatife Babajide and Babatunde Odebowale, thank you for your unfathomable supports. May God reward you abundantly.

I am highly indebted to all who in one way or the other assisted me during my Master's program. Your efforts are much appreciated. Lastly, my utmost appreciation to my family in Nigeria for believing in me and supporting me throughout the program. I'm proud of you all!

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1 INTRODUCTION

1.1 Background

The aim of fire protection is to minimize life safety risks, property damage, environmental impacts, and business interruptions. Life and fire safety strategies are designed to combat different fire scenarios depending on the classification of hazards in the building. Detection, control, and extinguishment of fires are achieved by a combination of active and passive fire protection systems [1]. Preventive measures such as early detection and elimination of ignition source are exigent especially at locations where highly flammable liquids and combustible materials are stored.

Active systems control fires through a device or action taken by a person. Some of these devices respond without human intervention while others require action by an operator to function. For example, an automated sprinkler system initiates suppression by itself or after receiving signals from a smoke or heat detector. Fire extinguishers such as stand pipe systems and portable systems are manually activated by an operator to suppress fires. Passive systems are materials that are built into the structure or fabric of a building without requiring specific operation in the event of a fire. For example, intumescent paints and concrete encasement are used to protect steel structures.

Fire is sustained whenever there is a continuous chemical reaction between the fuel, an oxidizing agent and sufficient heat. The four components, as shown in Figure 1.1, make up the fire tetrahedron. Fire extinguishment is achieved when one of these components is completely removed thereby eliminating the chemical reaction. Fuel is considered as any substance that could undergo combustion whether in solid, liquid or gaseous state. When sufficient heat is applied, it provides the minimum energy required to initiate ignition and also to maintain the release of pyrolysis products or flammable vapors. Oxidizing agents are typically oxygen from air or oxidants from combustible materials such as nitrates, chlorates and perchlorates, hydrogen peroxide and organic peroxides, and chlorine gas [2].

Figure 1.1 - Fire Tetrahedron [3]

Fire suppression is achieved when the rate of fuel-oxidation is reduced to a point below the flammability limit with the application of a suppressant or the environment cools below the minimum heat required to support flame propagation. A fire suppression agent can be discharged either manually or automatically via a portable system, fixed pipe system or hose system. The suppressing agent can be in the form of water, foam, chemicals or gases. The recommended fire suppression system for a building depends on the building occupancy and hazard classification.

1.2 Classes of fire

National Fire Codes categorize fires into five classes depending on the type of combustibles involved. The fire classifications are used to determine the level of occupancy hazards in buildings and the necessary fire suppression systems to be adopted. They are listed in NFPA 10- *Standard for Portable Fire Extinguishers [4]*, along with the classification of hazards. The classes of fire are:

1. **Class A Fires:** These are fires involving ordinary combustible materials, such as wood, cloth, paper, rubber, and many plastics.
2. **Class B Fires**: These are fires involving flammable liquids, combustible liquids, petroleum greases, tars, oils, oil-based paints, organic solvents, lacquers, alcohols, and flammable gases.
3. **Class C Fires**: These are fires involving energized electrical equipment.
4. **Class D Fires:** These are fires involving combustible metals, such as magnesium, titanium, zirconium, sodium, lithium, and potassium.
5. **Class K Fires:** These are fires involving combustible cooking media (vegetable or animal oils and fats).

1.3 Classification of Occupancy Hazard

Life and fire safety strategy of a building depends principally on the level of occupancy hazards and the importance of the items stored in the building. NFPA 10 [4] classifies occupancy hazards into three distinct groups. They are as follows:

a. **Light (Low) Hazards**: An occupancy is classified as a light hazard when it contains a minor quantity of Class A combustible materials such as furniture and a small quantity of Class B flammables that are safely stored in a closed container. This implies that majority of the items are either non-combustible or are arranged in a pattern that hinders rapid fire spread. Examples of such occupancies include churches, assembly halls, offices and so on.

b. **Ordinary (Moderate) Hazard:** An occupancy is considered as an ordinary hazard when the total amount of Class A combustibles and Class B flammables present are larger than the expected under low hazard occupancies. Such occupancies include dining areas, mercantile shops, and allied storage; light manufacturing, research operations, auto showrooms, parking garages, and workshops.

c. **Extra (High) Hazard:** Extra hazard occupancies are locations where the total quantity of Class A combustibles and Class B flammables present either in storage, production, use or as finished product are larger than the fuel load under moderate hazard occupancies. Examples are aircraft and boat servicing, cooking areas and warehouses.

The use of portable fire extinguishers is an important aspect of fire protection system in a building. They are fire safety equipment used to extinguish or suppress small fires before they become a threat to life and property. Substantial achievements have been recorded in the development of portable and handheld extinguishers over the last century. Since the combustible materials in a building govern the type of fire that could occur, choosing a suitable portable fire extinguisher is vital for the protection of life and property.

Choosing the appropriate portable fire extinguisher for the class of hazard depends on a careful analysis of the benefits and limitations (under various conditions) of the several types available. Likewise, total extinguishment of a small fire by a portable system depends on the expertise of the operator and the type of suppressant used. Existing portable fire extinguishers include water, dry powder, dry chemical, foam, and carbon dioxide.

While some of the existing portable foam extinguishers could encounter several limitations at the point of application such as poor foam quality and insufficient momentum to suppress the fire plume, research has shown that by incorporating compressed air into a foam system, the integrated foam system could generate superior quality of foam with high momentum when properly installed with the right components. Several studies had been conducted on the extinguishing performance of compressed air foam (CAF) systems on multiple fire types, both for small and large fires. For example, NRC Canada investigated the feasibility of using a fixed pipe compressed air foam (CAF) system for the protection of an aircraft hangar in place of a foam-water sprinkler system [5]. In other studies, Weinschenk et al [6] investigated the suppression capacity of CAF for interior firefighting. Overall, compressed air foam systems are used to protect equipment of various sizes because the foam expansion ratio could be regulated to combat specific fire types and sizes.

1.4 Statement of Problem

While diverse types of combustibles material are present in a building, they are used to estimate the amount of fire load and predict the potential fire hazard. They exist in the form of flammable gases, flammable liquids, interior finishes, metals, cooking oils, partitions, wood and so on. All these combustibles generate distinct types of fire and application of a wrong extinguisher on them might create a greater hazard. Some of the existing fire extinguishers are applicable to multiple fires but their suppression effectiveness and their adverse consequences after application remain a concern. For instance, water extinguishers are applicable on wood, paper, and cloth, which are primarily Class A combustible materials, but they could create injury hazards when used on electrical equipment, or in laboratories containing flammable liquids and combustible metals [4]. Water may contaminate chemical substances by reacting with them and could further damage water sensitive materials. Therefore, it is advisable to be utilized on only unreactive materials, ordinary combustible materials and in locations that do not require major clean-up. On the other hand, dry powder extinguishers are suitable for electrical equipment and combustible liquids but not applicable to cooking oil fires due to its poor cooling property [7]. Furthermore, the use of dry powder type fire extinguisher in large quantity might reduce visibility in the environment and would require a thorough clean-up process after application.

An advantage of the carbon dioxide extinguishers is their ability to discharge without leaving any residue after use. They are applicable to Class B and C fires. However, a significant deficit of these extinguishers is the exposure of the operator to heat during discharge operation due to its short-range coverage. Likewise, it endangers the safety of the operator when discharged in a confined area as the concentration required for fire suppression is high thereby reducing the oxygen concentration in the air. Also, a high concentration of carbon dioxide in a confined space would lead to suffocation of occupants if present. It is not effective in a windy environment as the agent evaporates rapidly during application thereby hindering total extinguishment.

Dry chemical extinguishers perform better under windy conditions but require a skilled operator to use. While some of the multi-purpose dry chemical extinguishers are suitable for Class A, B and C fires depending on the applied agent, residues of these agents such as potassium chloride on metal surfaces could cause corrosion [4]

Existing portable foam extinguishers generate fire-fighting foam at high pressures with the aid of an air-aspirating nozzle [8]. However, the system could encounter several limitations at the point of application such as poor foam quality and insufficient momentum to reach the seat of the fire. Kim & Crampton [9] compared the extinguishing performance of a manually operated CAF system with hose stream application of water only and water-foam solution on full-scale compartment fire tests. The results showed that the mobile CAF system was more effective in suppressing the fire when compared to the other two systems. The mobile CAF system generated superior quality foam with high momentum when properly installed with the right components. In addition, it reduced exposure of the operator to heat and provided faster knockdown of the fire plume as compared to air-aspirated foam because of its stronger stability and rheology.

1.5 Objectives

The aim of this study is to investigate the discharge characteristics, drainage characteristics and the fire suppression performance of a portable compressed air foam system. The study also investigates compliance with the requirements of NFPA 10 [4] and CAN/ULC-S508-M90 [10] for a new portable system. The objectives of the project research are:

1. To investigate the discharge characteristics of a portable CAF system
2. To investigate the drainage characteristics of the foam with and without thermal radiation
3. To investigate the suppression capability of the system on wood crib fires
4. To investigate the extinguishing performance of the system on pool fires

In the subsequent chapters, literature review is discussed in Chapter 2, methodology of the tests in Chapter 3, results and discussion in Chapter 4, conclusions and recommendations in Chapter 5, while an additional diagram is provided in Appendix A.

2 LITERATURE REVIEW

In this chapter, a review of the theoretical background of portable fire extinguishers as well as research works by others on fire suppression and drainage characteristics of a compressed air foam system are presented.

2.1 Portable Fire Extinguisher

Portable fire extinguishers are handheld systems containing an extinguishing agent that is discharged under pressure for suppressing or extinguishing fires. They may be carried by hand or installed on wheels. Portable fire extinguishers are classified for use on fire based on the fire classification and fire extinguishment potential as determined by fire tests. They are rated for relative extinguishing effectiveness at a temperature of 21ºC by testing laboratories. The classification and rating system of portable fire extinguishers used in Canada is that of Underwriters Laboratories Inc. and Underwriters Laboratories of Canada. Fire tests for portable fire extinguisher are regulated by the following standards; CAN / ULC-S508 [10] and ANSI / UL 711 [11] while the extinguishing performance must meet the criteria listed in ANSI/UL 8 [12] for foam types.

The rating for a specific portable fire extinguisher is located on its label. In Canada, the UL rating is broken down into Class A and Class B:C ratings. These ratings are used to compare the relative extinguishing effectiveness of different fire extinguishers. For example, a portable fire extinguisher with a rating of 4A:20B:C indicates the following:

1. The A rating stands for water equivalency rating. Each A is equivalent to 1 ¼ gallon of water. Therefore, 4A = 5 gallons of water.
2. The B rating is equivalent to the amount of square footage that the extinguisher can cover when handled by a professional. 20 B means 20 square feet of coverage.

3. C implies that the system is suitable for use on electrically energized equipment.

2.2 Types of Portable Fire Extinguishers

Selecting the most suitable fire suppression system for different hazard classifications depend on the critical evaluation of the benefits and limitations of the available types. Existing portable fire extinguishers include water, dry powder, dry chemical, foam, and carbon dioxide. The characteristics of the existing portable fire extinguishers as reviewed in NFPA 10 [4], *Standard for portable fire extinguisher*, are discussed below.

a) **Water-Type Fire Extinguishers:** These include water, antifreeze, wetting agent and loaded stream fire extinguishers. They are primarily used for Class A fires. Their mode of operation is by discharging the water stream to the base of the flames, then directly to the smoldering or glowing surfaces. Water is applied as close as possible to the fire. Deep-seated fires are flooded with water for complete extinguishment.

   i. Stored-Pressure Water Extinguishers: They are available in 9.46 L (2.5 gal) capacity with a fire extinguishment rating of 2-A. The fire extinguisher has a solid stream horizontal range of approximately 10.7 m to 12.2 m. It has an application time of 55 s under continuous use. This type of fire extinguisher cannot be installed in areas subjected to temperatures below 4ºC as the extinguishing agent, fresh water, would become ineffective. However, it can be manufactured in an antifreeze model charged with an approved solution that would provide protection to temperatures as low as -40ºC.

   The fire extinguisher is protected by using a ring pin thereby leaving the operating lever in a locked position to prevent accidental discharge. For its mode of operation, the ring pin is first pulled out before the operating lever can be depressed.

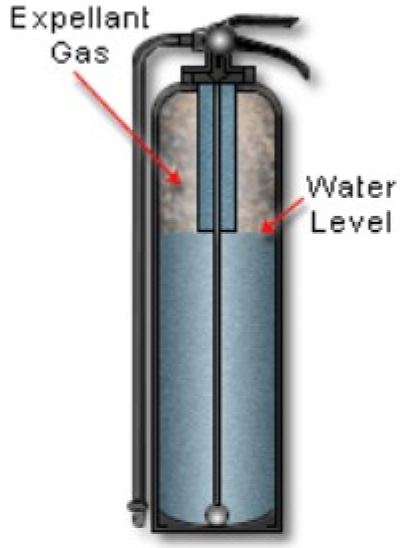


Figure 2.1 - Stored-pressure water extinguisher [13]

ii. Loaded Stream Extinguishers: They are available in different sizes ranging from 3.8 L to 9.46 L (1- 2.5 gal) capacity at ratings of 1-A:1-B to 3-A:1-B. These fire extinguishers are no longer listed for use on Class B fires due to their limited effectiveness. However, wheeled fire extinguishers have been manufactured with capacities of 64 L and 125 L (17 gal and 33 gal) with fire extinguishment ratings of 10-A to 20-A. The chemical used is a solution of an alkali metal salt that will not freeze at temperatures as low as -40ºC.

iii. Pump Tank Extinguishers: They are available in different sizes ranging from 5.7 L to 19 L (1.5 gal to 5 gal) capacity at ratings of 1-A to 4-A. However, the most common type is 9.46 L (2.5 gal) rated at 2-A. These are made of cylindrical metal containers with carrying handles. In some models, the carrying handle is combined with the pump handle, and in others, it is attached to the container. A built-in, hand-operated vertical piston pump, to which a short rubber hose and nozzle are attached, provides the means for discharging the water unto the fire. The pump is of the double acting type, which discharges a stream of water on both the up and down strokes. When brought to a fire, the pump tank is placed on the ground and, to steady the unit, the operator puts one foot on a small extension bracket attached to the base. To force the water through the hose, the operator then pumps the handle up and down. To work around the fire, or to move closer to the fire as the flames subside, the operator needs to stop pumping and carry the fire extinguisher to a new location. The force, range and duration of the stream are dependent, to a degree, on the operator.

They can be filled with either plain water or antifreeze charges as recommended by the fire extinguisher manufacturer. Common salt or other freezing depressants could corrode the fire extinguisher, damage the pump assembly, or affect the fire extinguishing capability. Copper shell and nonmetallic models do not corrode as easily as steel and are recommended for use in conjunction with antifreeze agents.

iv. Backpack Extinguishers: They are used for fighting outdoor fires in brush and wildlands. The tank capacity when full is 19 L (5 gal) and weighs approximately 23 kg. It does not have a designated rating although it is listed by UL. Plain water is the common extinguishing agent for this fire extinguisher. However, antifreeze agents, wetting agents or other special water-based agents can be used. It is designed to be carried on the operator's back and the tank can be constructed of fiberglass, stainless steel, galvanized steel or brass.

The backpack fire extinguisher has a large opening for fast refilling as well as a tight-fitting filter to prevent foreign materials from entering and clogging the pump. The design permits for convenient refilling from nearby water sources such as ponds, lakes or streams. Discharge occurs when the operator, holding the pump in both hands, moves the piston section back and forth. Models have been manufactured with compression pumps mounted on the right side of the tank while expellant pressure is built up with 10 strokes of the handle and then maintained by continual slow, easy pumping strokes. Discharge is controlled with the left hand by means of a lever operated shut off nozzle attached to the end of the hose. The most commonly used model has a trombone-type, double acting piston pump connected to the tank by a short length of rubber hose.

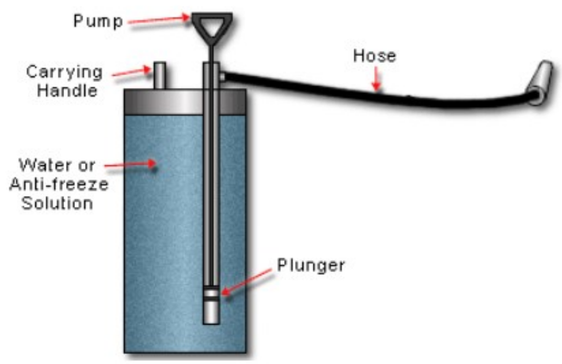


Figure 2.2 - Floor Model Pump Tank Fire Extinguisher [13]

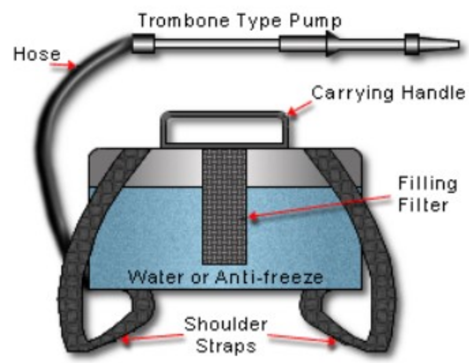


Figure 2.3 - Backpack Pump Tank Fire Extinguisher [13]

v. Wetting Agent Extinguishers: They are available in hand portable models of 5.7 L (1.5 gal) capacities and in wheeled models having liquid capacities of 170 L and 228 L (45 gal and 60 gal) with ratings of 2-A, 30-A, and 40-A respectively. The extinguishing agent used is a surface-active material added to water in proper quantities to materially reduce the surface tension of the water thereby increasing penetrating and spreading characteristics. Hand portable models are operated similarly to other stored-pressure types while wheeled extinguishers are operated by a separate carbon dioxide cartridge containing the expellant gas which, when released, expels the agent through the hose nozzle.

b) **Foam Type Fire Extinguishers:** Portable Fire extinguishers using film-forming foam agents (FFF) are applicable on Class A and Class B fires. For Class B fires, the discharge from the fire extinguisher is applied against the inside of the back wall of the vat or tank just above the burning surface to allow the natural spread of the suppressant over the burning liquid. If this is impossible, the suppressant should be applied in such a way that it would fall lightly upon the burning surface. The operator stands at a distance from the fire and walks around the fire while directing the stream in such a way that maximum coverage is achieved during the discharge period. For Class A fires involving ordinary combustible materials, the suppressant could be used to coat the burning surface directly while for flammable liquid fires, the agent could be flowed over a burning surface by bouncing it off the floor just in front of the burning area. However, FFF agents are not effective on flammable liquids and gases escaping under pressure or cooking grease fires.

i. AFFF and FFFP Agents: Fire extinguishers of these types are available in hand portable models of 6 L (1.6 gal) and 9.46 L (2.5 gal) and in wheeled models having liquid capacities of 125 L (33 gal) with ratings of 2-A, 10-B, 3-A:20-B and 20-A:160-B respectively. The extinguishing agent is a solution of film-forming surfactant in water that generates fire-fighting foam when discharged through an aspirating nozzle. On Class A fires, the agent acts as both a coolant and penetrant to reduce temperatures to below the ignition level. On Class B fires, the agent acts as a barrier to exclude air or oxygen from the fuel surface. Furthermore, these agents are suitable for polar solvents such as alcohols, acetone, esters, ketones and so on but unsuitable for use on pressurized fuel fires or cooking grease fire. The suitability of these fire extinguishers on water-soluble flammable liquids (polar solvents) is specifically referenced on the nameplate.

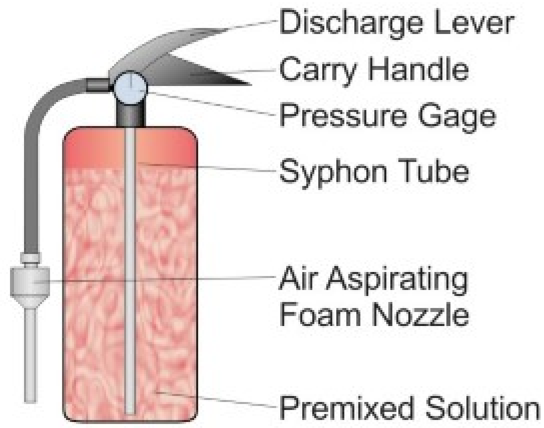


Figure 2.4 – Foam Type Fire Extinguisher [13]

Wheeled types are operated by a separate nitrogen cylinder containing the expellant gas which, when released, pressurizes the agent container. The discharge is controlled by a special aspirating shutoff type of nozzle at the end of the hose assembly. These types of fire extinguishers can be used only in locations not subject to freezing conditions unless specific measures recommended by the manufacturer are provided to prevent the agent from freezing

c) Carbon Dioxide Type: It is applicable for use on Class B and Class C fires. Carbon dioxide fire extinguishers have a limited range and are affected by draft and wind. Therefore, the agent is directed towards the base of the fire at a close range. Furthermore, the discharge is applied on the burning surface after the fire had been extinguished in order to prevent re-ignition. The most common mode of operation on contained flammable liquid fires is aimed at the near edge and toward the back of the fire in a slow, side-to-side sweeping technique. The second method is known as an overhead application. Its mode of operation is by directing the discharge horn in a dagger or downward position (at an angle of about 45 degrees) toward the center of the burning area. Unlike the former method, the horn is not moved because the discharge stream enters the fire from above and spreads out in all directions over the burning surface. For spill fires, the side-to-side sweeping motion could give better results. On Class C fires, the discharge is directed at the source of the flame. It is important to de-energize the electrical equipment as soon as possible to eliminate the potential of reignition. However, these agents are not suitable for use on pressurized fuel fires or cooking grease fires.

Carbon dioxide agent suppresses by diluting the surrounding atmosphere with an inert gas so that the oxygen level is kept below the percentage required for combustion. If used in an unventilated space or confined area, prolonged occupancy of that space could result in the loss of consciousness due to oxygen deficiency.

Portable fire extinguishers using carbon dioxide as an agent are usually available at capacities from 1.1 kg to 9.1 kg with fire extinguishment ratings from 1-B:C to 10-B:C while wheeled carbon dioxide fire extinguishers are available in capacities from 23 kg to 45 kg with ratings from 10-B:C to 20-B:C. The carbon dioxide is stored under pressure at room temperature. The agent is self-expelling and is discharged by operation of a valve that causes the carbon dioxide to be expelled via a horn. To operate this fire extinguisher, it is held in an upright position, the locking ring pin is pulled, and the operating lever is squeezed. For smaller models of 0.91 kg to 2.3 kg, the discharge horn is attached to the valve assembly by a metal tube/swing joint connector. The smaller models are designed to be operated with one hand. On the larger hand portables, the discharge horn is attached to several feet of flexible hose and it requires two hand operation. The minimum discharge time for hand portables varies from 8 seconds to 30 seconds, depending upon size. The maximum range of the discharge stream is from 1 m to 2.4 m (3 ft to 8 ft).

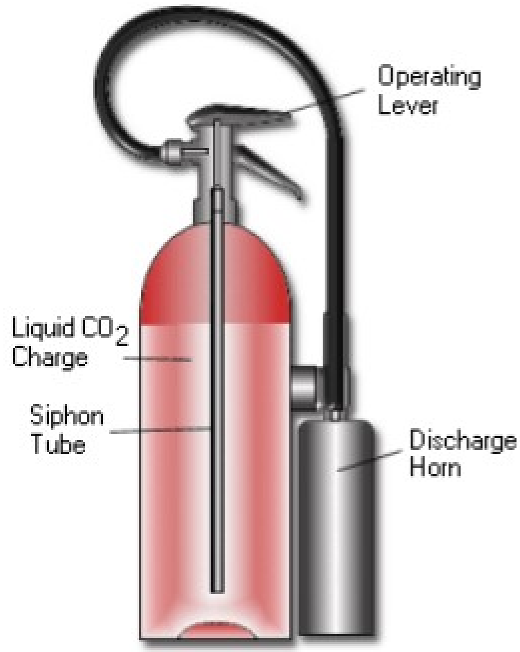


Figure 2.5 - Carbon Dioxide Fire Extinguisher [13]

d) **Dry Chemical Types:** Dry chemical fire extinguishers (multipurpose ammonium phosphate base) are applicable for use on Class A, Class B, and Class C fires. The two methods of discharging dry chemical agents from a fire extinguisher shell, depending on the basic design of the fire extinguisher, are the cartridge/cylinder-operated method and stored-pressure method. The mode of operation for both methods is the same. Stored-pressure fire extinguishers are available in capacities from 0.5 kg to 14 kg for hand fire extinguishers and 57 kg to 113.5 kg for wheeled fire extinguishers. Cartridge/cylinder-operated fire extinguishers are available in capacities from 1.8 kg to 14 kg for hand fire extinguishers and 20 kg to 159 kg for wheeled fire extinguishers.

Dry chemical fire extinguishers are also available in non-rechargeable, non-refillable types that contain the agent and expellant gas in a single, non-reusable, factory-filled container. Specialty is required when operating this type of fire extinguisher since the majority of the dry chemical fire extinguishers with a rating of 20-B and less will discharge their contents in 8-20 seconds while fire extinguishers with higher rating could take as long as 30 seconds. All dry chemical fire extinguishers can be operated simultaneously and discharged intermittently. The discharge stream has a horizontal range of 1.5 m to 9.2 m depending on its size. For outdoor fires, maximum effectiveness is achieved when it's not affected by wind.

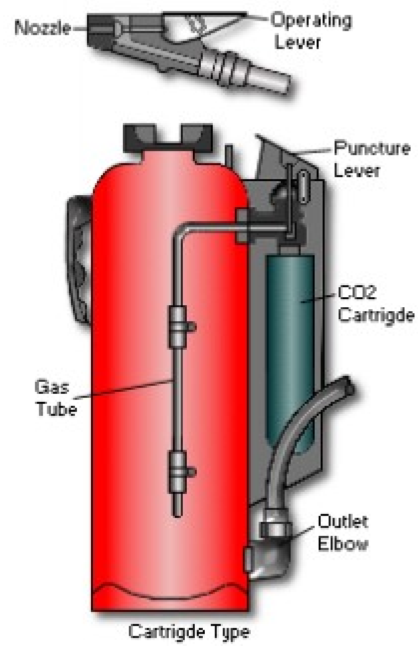


Figure 2.6 - Dry Chemical Type Fire Extinguisher [13]

Special long-range nozzles are available for potential fire-fighting conditions that would require greater distance. Also, the nozzles are useful on pressurized gas or liquid fires, or where strong wind prevails. All dry chemical agents can be applied simultaneously with water (straight stream or fog). The use of dry chemical fire extinguishers on wet energized electrical equipment, such as rain-soaked utility poles, high-voltage switch-gear, and transformers, can aggravate electrical leakage problems. The dry chemical, in combination with moisture, provides an electrical path that can reduce the effectiveness of insulation protection. The removal of all traces of dry chemical from such equipment after extinguishment is recommended. Fire extinguishers with a Class B rating can extinguish a fire involving combustible cooking media (vegetable or animal oils and fats) while fire extinguishers with a Class K rating are recommended for use on cooking grease fires

i. Ordinary Dry Chemical Extinguishers (Class B and Class C Fires): Portable fire extinguishers of this type are available with fire extinguishing ratings of 1-B:C to 160-B:C and wheeled models having fire extinguishment ratings from 80-B:C to 640-B:C. Types of agent in this category are sodium bicarbonate base, potassium bicarbonate base, potassium chloride base, or potassium bicarbonate urea base. Quick extinguishment is achieved when the stream of the discharge is directed at the base of the flames on flammable liquid fire. The near edge of the fire is first attacked before progressing towards the back of the fire by moving the nozzle rapidly with a side-to-side sweeping motion.

ii. Multipurpose Dry Chemical Fire Extinguishers (Class A, Class B, and Class C fires): It contains an ammonium phosphate base agent. Portable fire extinguishers are available with fire extinguishment ratings of 1-A to 20-A and 10-B:C to 120-B:C and wheeled models with fire extinguishment ratings of 20-A to 40-A and 60-B:C to 320-B:C. The multipurpose agent has the additional characteristics of softening and sticking when in contact with hot surfaces. In this way, it can adhere to burning materials and form a coating that will smother and isolate the fuel from air. However, extinguishment of deep-seated fires with multipurpose dry chemical fire extinguishers could possibly not be accomplished unless the agent is discharged below the surface or the material is broken apart and spread out.

e) **Dry Powder Extinguishers:** They are available in a hand portable 14 kg cartridge-operated wheel models, 68 kg and 159 kg cylinder-operated wheeled models. The suppressant consists of sodium chloride, with additives for free flowing to form a crust over the fire. A thermoplastic material is added to bind the sodium chloride particles into a solid mass when applied on burning metals. Other specialized dry powder agents are available for use in fighting specific types of metal fires. The model has a range of 1.8 m to 2.4 m when the nozzle is fully opened.

i. Bulk Dry Powder Agent: Fire extinguishers of this type are available in 18 kg pails and 159 kg drums. Aside the sodium chloride agent, a dry powder material called G-1 which comprises of graded and granular graphite is added to improve the fire extinguishing effectiveness. The sodium chloride can be used in a dry powder fire extinguisher or applied by shovel or hand scoop while the G-1 agent is applied to the fire by hand. When G-1 is applied to a metal fire, the heat of the fire causes the phosphorus compounds to generate vapors that blanket the fire and prevent air from reaching the burning metal. The graphite being a good conductor of heat, cools the metal to below the ignition point. Dry powder extinguishing agents must not be confused with dry chemical extinguishing agents.

2.3 Fire-fighting foam

Fire-fighting foam is used as a fire protection, control, or extinguishing agent for flammable liquid hazards. It is a stable aggregate of air-filled bubbles, generated from aqueous solutions, of lower density than flammable liquids and dispersed by means of specially designed equipment.

Fire-fighting foam suppresses liquid pool fires by forming a cohesive floating blanket on the burning surface that isolates the fuel from air. Re-ignition is prevented by suppressing the formation of flammable vapors and resisting the effect of external forces such as wind, flame attack or heat.

Fire-fighting foams can retain their properties for a long duration. They are classified into three ranges of expansion foam depending on their usage [14]. Expansion foam is the ratio of the volume of expanded foam to the volume of the foam solution. The three ranges are as follows:

a) **Low Expansion Foam** - Expansion up to 20

They are suitable for flammable liquid fires. Low expansion foam has proven to be an effective means of controlling and extinguishing Class B fires (flammable liquid fires) due to their good spreading capability. They are also used on Class A fires due to their wetting properties especially where the cooling and penetrating effect of the foam solution is crucial [15].

b) **Medium Expansion Foam** – Expansion from 20 to 200

Medium expansion foams are used to suppress the vaporization of hazardous chemicals when exposed to fire. After a series of test, expansion foams between 30:1 and 55:1 were discovered to produce the optimal foam blanket for vapor mitigation of highly water reactive chemicals and low boiling organics [15].

c) **High Expansion Foam** – Expansion from 200 to 1000

High-expansion foam provides good extinguishing capacity for three-dimensional fires such as confined space firefighting. It is used on fires that propagate both upwards and downwards. High expansion foam concentrate is a synthetic, detergent-type foaming agent used in confined spaces such as basements, mines, and shipboard when used in combination with a high expansion foam generator [15].

2.4 Types of Foam Concentrate

Fire-fighting foams are aggregations of mechanically generated bubbles formed from the passage of air through a mixing mechanism containing product of foam concentrate and water. Foam concentrates are designed to be mixed with water at specific ratios as prescribed by the manufacturer while foam solution is a homogeneous mixture of water and foam concentrate in desired proportions. To achieve a 3% foam solution, 97 parts of water are mixed with 3 parts of foam concentrate. The commonly used foam concentrates are the following:

a) **Protein-Foam (RP)**: Regular Protein foams (RP) are intended for use on hydrocarbon fuels only. They produce a homogeneous, stable foam blanket that has excellent heat resistance, burn-back, and drainage characteristics. Regular Protein foams have slow knockdown characteristics; however, they provide superior post-fire security. Regular protein foams may be used with fresh or sea water. They must be properly aspirated and should not be used with non-aspirating structural fog nozzles.

   Protein foams were the first types of mechanical foams to be marketed extensively and have been used since World War II. These foams are produced by the hydrolysis of granulated keratin protein (protein hydrolysate) such as hoof and horn meal, chicken feathers, etc. In addition, stabilizing additives and inhibitors are included to prevent corrosion, resist bacterial decomposition and to control viscosity [15]. They are diluted with water to produce 3% to 6% solution depending on its type. These concentrates are compatible with certain dry chemicals [14].

b) **Fluoroprotein-Foam (FP):** Fluoroprotein foams have fluorochemical surfactants which greatly enhance performance with a fast knockdown, improved resistance to fuel pick-up, and dry chemical compatibility. They are intended for use on hydrocarbon fuels and selected oxygenated fuel additives. With similar property to protein, they have excellent heat resistance, burn-back, and post-fire security. Fluoroprotein foams may be used with fresh or sea water. They extinguish by creating a foam blanket on the burning surface. Also, they prevent the formation of a film on the surface of a liquid fuel.

   Fluoroprotein foams are made by the addition of special fluorochemical surfactants to protein foam. This enhances the properties of protein foam by increasing foam fluidity and improves the properties of regular protein foam by providing faster knockdown and excellent fuel tolerance. They are mixed with water to form 3-6% foam solutions [15].

c) **Film-Forming Fluoroprotein Foam (FFFP):** They are used to suppress hydrocarbon fuel vapors by producing a fluid aqueous film from fluorinated surfactants. This type of foam utilizes a protein base plus stabilizing additives and inhibitors to protect against freezing, corrosion, bacterial decomposition and resists fuel pickup. FFFP's are a combination of fluorochemical surfactants with protein foam.

   They are designed to combine the fuel tolerance and burnback resistance of a fluoroprotein foam with an increased knockdown power. FFFP foams release an aqueous film on the surface of the hydrocarbon fuel. The foam is dry chemical compatible and is usually diluted with water to 3% or 6% solutions.

d) **Aqueous Film Forming Foam (AFFF):** They are designed to provide the fastest possible knockdown on hydrocarbon fuels. AFFF's are a combination of fluorochemical surfactants and synthetic foaming agents. AFFF's extinguish fires by removing oxygen and forming an aqueous film on the fuel surface. This film is a thin layer of foam solution that spreads rapidly across the surface of a hydrocarbon fuel causing fast fire knockdown. Furthermore, the aqueous film reduces the surface tension of the foam solution to a point where the solution can be supported on the surface of the hydrocarbon. AFFF concentrates are diluted with water to a 1%, 3% or 6% solution. The foam produced with AFFF concentrate is dry chemical compatible and therefore can be combined with dry chemical.

e) **Alcohol Resistant Aqueous Film Forming Foam (AR-AFFF):** Alcohol resistant-AFFF foams are produced from a combination of synthetic detergents, fluorochemicals, and polysaccharide polymer. Polar solvents (or water miscible) fuels such as alcohols are destructive to non-alcohol resistant type foams. Alcohol resistant-AFFF foams act as a conventional AFFF on hydrocarbon fuels, forming an aqueous film on the surface of the hydrocarbon fuel. When used on polar solvents (or water miscible fuels), the polysaccharide polymer forms a tough membrane which separates the foam from the fuel and prevents the destruction of the foam blanket. While some concentrates are designed for use on hydrocarbon fuels at 3% and polar solvents at 6%, recent formulations are designed to be used at 3% on both fuel groups. These formulations provide a more cost-effective protection for alcohol type fuels, using half the amount of concentrate as a 3% / 6% agent. The 3% concentrate for both hydrocarbon fuels and polar solvent makes proportioning of concentrate easy. Overall, AR-AFFF's are the most versatile type of foam available today, offering good burn-back resistance, knockdown and high fuel tolerance on both hydrocarbon and polar solvent (or water miscible) fires.

f) **Alcohol Resistant Film Forming Fluoroprotein Foam (AR-FFFP):** Alcohol resistant-FFFP foams are produced from a combination of protein foam, fluorochemical surfactants, and polysaccharide polymer. AR-FFFP foams act as conventional FFFP's on hydrocarbon fuels by forming an aqueous film on the surface of the hydrocarbon fuel. When used on polar solvents (or water miscible fuels), the polysaccharide polymer creates a tough membrane which separates the foam from the fuel and prevents the destruction of the foam blanket. AR-FFFP foams are available as 3% / 6% concentrates which are designed for use on hydrocarbon fuels at 3% and polar solvents at 6%. These formulations are also available for use at 3% on both hydrocarbons and polar solvent fuels.

g) **Synthetic Detergent Foam (Mid and High Expansion):** They are derived from hydrocarbon surfactants and are used in specially designed equipment to produce foams with an expansion ratio of 1:20 to 1:1000. Synthetic foams are a mixture of synthetic foaming agents and stabilizers. Mid-Expansion of synthetic detergent-based foams are used for suppressing hazardous vapors. However, specific foams are required depending on the chemicals involved.

High expansion foam is a very wetting agent and is highly effective on Class A fires. High expansion foams are used in fixed installations to provide total flooding of warehouses or other enclosed rooms containing Class A materials such as wood, paper, plastic, and rubber. It operates differently when compared to low expansion foam by smothering the fire area and cooling the fuel. It is an effective suppressant for confined space fires. High expansion foams can also be used on small scale class B hydrocarbon fires.

2.5 Method of Foam Application

Fire-fighting foams are applied by either fixed pipe systems, foam hand hoseline systems or portable foam-generating systems.

2.5.1 Fixed Pipe System

The foam is supplied by overhead piped systems for protection of large areas and hazardous occupancies associated with potential flammable liquid spills which are close to high-value equipment as shown in Figure 2.7. The foam used is in the form of a spray or dense "snowstorm" for flammable liquid spills. The foam particles coalesce on the surface of the burning fuel after falling from the overhead foam outlets. The outlets are positioned to cover the entire area at a uniform density. The fixed pipe systems are used for the protection of aircraft hangars. The code responsible for the protection of aircraft hangars, NFPA 409 [16] recommends the use of foam monitor system, high expansion foam system, and overhead foam-water sprinkler system. They can be implemented separately or two systems can be used together to provide optimal protection to aircrafts and other facilities.

Figure 2.7 - High Expansion Foam System Protection for Syracuse Military Aircraft Hangar [17]

2.5.2 Foam Hand Hose Line System

The system operates by passing a water stream through foam concentrate and ejecting the finished foam via a discharged device as shown in Figure 2.8. Water is passed at high pressure through a proportioning device which simultaneously picks up foam concentrate and mixes it with the water stream to produce the desired foam solution. The foam concentrate passes through a metering valve which allows the correct percentage to be introduced into the water stream. In most cases, the metering valve can be adjusted to select a 1, 3, or 6% foam solution. This system is used as a supplementary protection in aircraft hangars. Also, mobile equipment such as an aircraft crash truck or industrial foam truck equipped with agent and equipment capable of generating large volumes of foam at high rates are used to deliver foam as a solid stream or in a dispersed pattern.

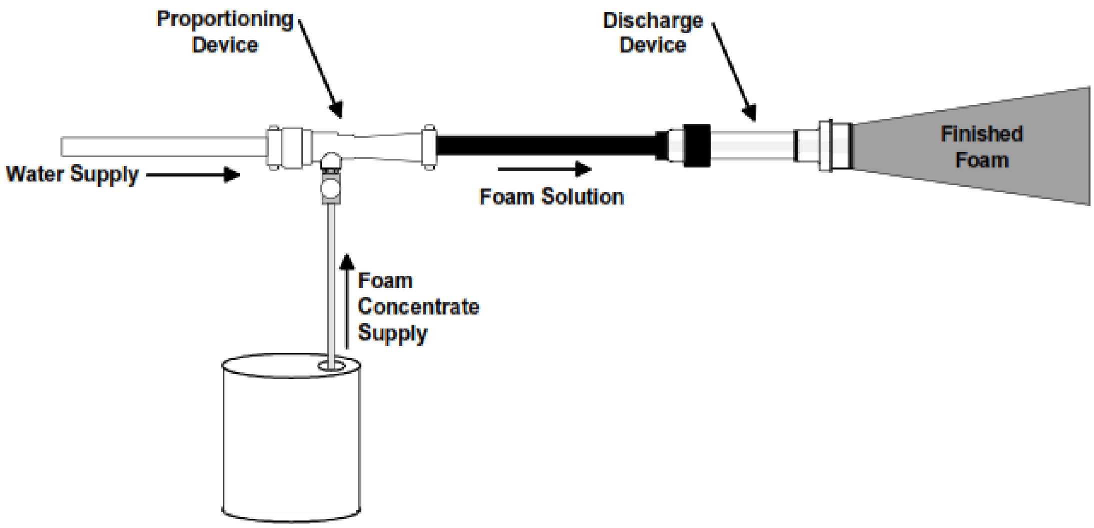


Figure 2.8 - Systematic Diagram of Foam Hand Hose Line System [15]

2.5.3 Portable Foam System

The two common methods for generating foam are nozzle-aspirated foam systems and compressed air foam systems (CAFs). The quality of the generated foam depends on the proportion of water, foam concentrate and air.

i. Nozzle-Aspirated Foam Delivery Systems (NAFS): The foam concentrate is pre-mixed with water inside a pressurized container to create foam solution. The foam solution is delivered to the nozzle, where it is aerated to generate foam. This system operates at high pressures to discharge foam at a short duration [8].
ii. Compressed Air Foam Systems (CAF): The CAF generating system consists of an air compressor, water and foam concentrate. Water is premixed with foam concentrate inside a pressurized container at a desired proportion to create foam solution while compressed air is injected into the foam solution to aerate it afterwards. The generated foam passes through a hose where it keeps developing before it is discharged through a nozzle. Unlike the nozzle-aspirated foam system which generates foam at the nozzle, the compressed air

foam system develops foam inside the hose. Hence, the hose-line conveys a higher proportion of air to water which makes it lighter and more flexible than plain water hose-line [18].

2.6 Fire-fighting Foam Properties

Fire-fighting foam is considered effective when it possesses the right blend of some physical characteristics that make it form a cohesive blanket. The characteristics are as follows:

a) **Knockdown Speed and Flow**: It is the time taken for a foam blanket to cover a fuel surface or combustible materials in other to achieve complete extinguishment.

b) **Heat Resistance**: It is the ability of the foam to resist the destructive effects of radiated heat from a pool fire or any combustible material in the environment.

c) **Fuel Resistance**: This measures the ability of the foam to minimize fuel pick-up so that the foam does not become saturated with fuel and eventually aid combustion.

d) **Vapor Suppression**: The produced vapor-tight foam blanket must be able to effectively suppress the flammable vapor and reduce the possibility of re-ignition.

e) **Alcohol Resistance**: A suppressing agent that does not possess alcohol-resistant properties would be destroyed when used to extinguish an alcohol affiliated fuel.

Table 2.1: Properties and comparisons of fire-fighting foams [15]

Property	Protein	Fluoroprotein	AFFF	FFFP	AR-AFFF
Knockdown	Fair	Good	Excellent	Good	Excellent
Heat Resistance	Excellent	Excellent	Fair	Good	Good
Fuel Resistance (Hydrocarbons)	Fair	Excellent	Moderate	Good	Good
Vapor Suppression	Excellent	Excellent	Good	Good	Good
Alcohol Resistance	None	None	None	None	Excellent

2.7 Foam Characteristics

The physical characteristics of foam depends upon the concentration of the foam solution, type of foam concentrate used, hose length, nozzle type and means of aeration. Hence, fire-fighting foam is characterized as wet, fluid or dry [18].

a) **Wet foam:** Wet foams are characterized by smaller bubbles comprising of closely packed polyhedral cells, low expansion and fast drain times at ambient temperature. Wet foams are suitable for initial fire suppression, overhaul and penetration into deep-seated fires
b) **Fluid foam:** Fluid foam is in the form of a watery shaving cream with small to medium bubbles, medium expansion and moderate drain times at ambient temperature. Fluid foam is suitable for direct attack and exposure protection
c) **Dry foam:** Dry foam has the consistency of a shaving or whipped cream of high expansion foam. It is very fluffy and consists mainly of air. Dry foams have slow drain times at

ambient temperature and retain their shape for a long duration. Dry foam is suitable for heat exposure protection of structures because of its ability to cling to vertical surfaces for extended periods.

2.8 Review of Pertinent Literature on Compressed Air Foam System

Many studies had been conducted on several aspects of the compressed air foam system such as fire extinguishing performance, heat penetration, and drainage characteristics. Relevant researches on the compressed air foam characteristics are presented in this section.

Suppression of Wood Crib Fires with Sprinkler Sprays [19]

Authors: William D. Walton

The extinguishing performance of sprinkler water sprays on two sizes of wood cribs was investigated. Both wood crib sizes were constructed of fir stacks 1.5 inches (38 mm) high by 1.5 inches (38 mm) wide and 2 ft (0.61 m) long. The sticks were fastened together with 8d common nails at both ends. The overall crib sizes were 2 ft (0.61 m) wide 2 ft (0.61 m) deep with 6 sticks per layer. Two different heights were used, 1 ft (0.3 m) high with 8 layers of sticks and 2 ft (0.61 m) high with 16 layers. The 16 layers crib comprised of two of the 8 layers stacked one on top of the other. The 8 layers and 16 layers cribs were referred to as single height crib and double height crib respectively. The cribs were placed on 102 mm high concrete blocks and the ignition source used was 600 ml of heptane. The sprinkler head was positioned at 95.75 inches (2.43 m) above the floor. The burning time of the heptane was approximately 120 seconds. Table 2.2 gives the results of the wood crib tests.

Table 2.2: Results of the wood crib test [19]

	Density							
	Low (gpm/ft^2)	High (gpm/ft^2)	Average (gpm/ft^2)	Average (mm/min)	Time* (s)	Total Water (gal/ft^2)	Crib Weight (lbs)	Distance from sprinkler to Crib (in.)
Single Cribs	free burn						45.9	
	0.020	0.021	0.020	0.82	1270	0.423	45.1	66
	0.033	0.045	0.039	1.59	1200	0.780	54.2	94
	0.054	0.060	0.058	2.36	700	0.676	46.4	66
	0.055	0.066	0.061	2.49	480	0.488	44.1	69
	0.046	0.106	0.078	3.18	730	0.949	46.7	69
	0.075	0.091	0.084	3.42	510	0.714	44.1	69
	0.091	0.107	0.099	4.03	270	0.446	55.0	66
	0.112	0.126	0.119	4.85	230	0.456	54.9	66
	0.112	0.141	0.126	5.13	240	0.504	54.6	66
	0.105	0.154	0.130	5.30	140	0.303	47.0	94
	0.169	0.205	0.196	7.99	100	0.326	50.4	66
Double Cribs	free burn						96.6	
	0.020	0.023	0.021	0.86	1151	0.403	95.7	66
	0.054	0.060	0.058	2.36	1240	1.199	89.4	66
	0.091	0.103	0.097	3.95	1140	1.843	104.5	66
	0.113	0.126	0.119	4.85	830	1.646	105.6	66
	0.112	0.133	0.124	5.05	750	1.550	107.0	66
	0.156	0.208	0.186	7.58	500	1.550	97.5	66

*Time over which water was applied during the test.

The results show the spray densities, flow rate, application time and duration for each test. The crib weight also includes the weight of the nails used in constructing the cribs. The results indicate that the higher the flow densities, the less the application time and water used.

The time from ignition to spray application, which is referred to as the pre-burn time, was about 330 seconds. The pre-burn time was longer in some tests to achieve complete wood crib involvement. The free burn heat release rate for the single and double cribs along with a single and double crib sprinkler test each with a density of 0.119 gpm/ft^2 (4.85 mm/min) is shown in Figure 2.9.

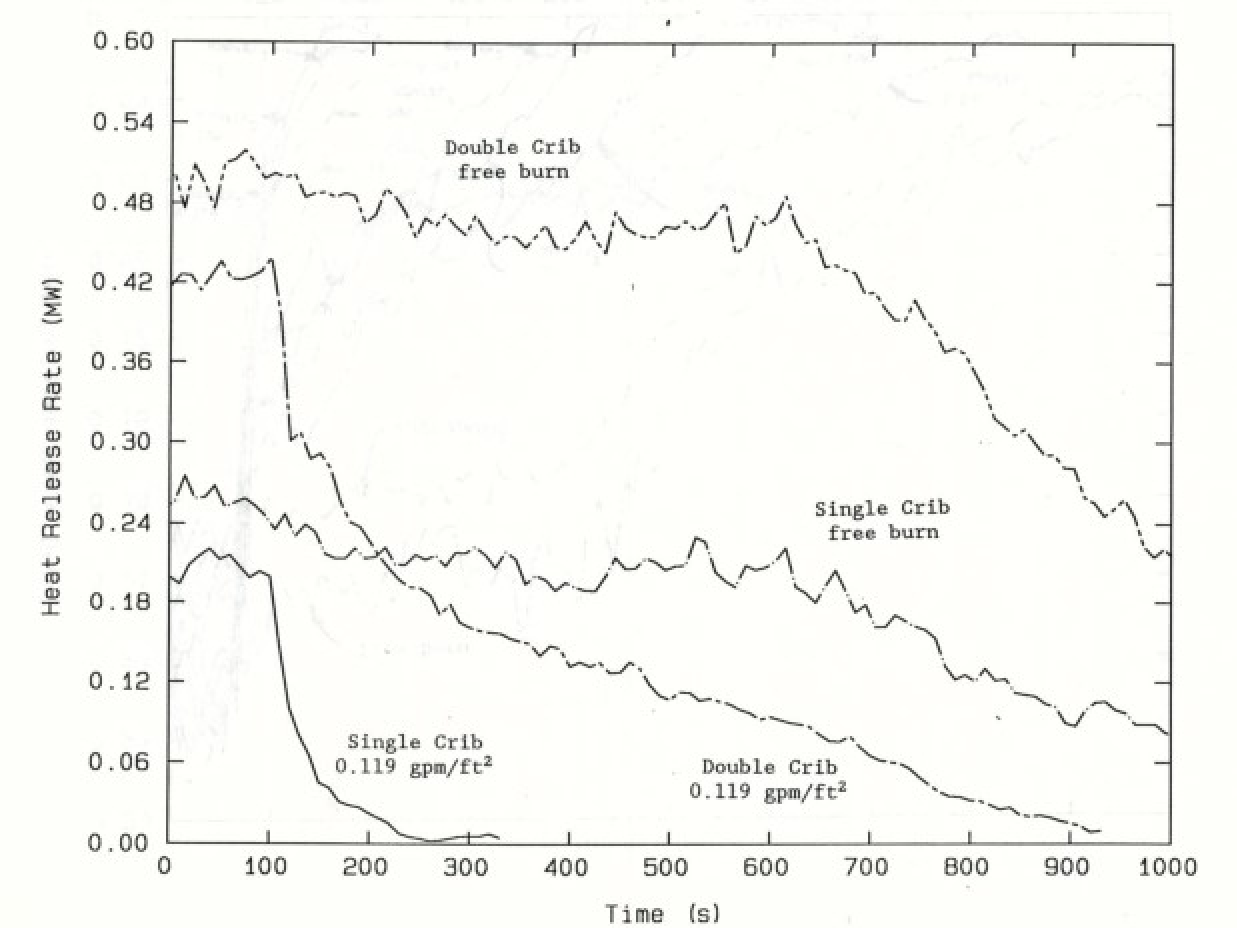


Figure 2.9 - Heat Release Rate of Single and Double Crib with time [19]

The heat release rate (HRR) at the time of spray application ranged from 0.2 to 0.27 MW for the single crib and from 0.42 to 0.50 MW for the double crib. A rapid drop in HRR was observed after activating fire suppression for both sprinkler tests, followed by gradual reduction as water drips down the crib. The initial reduction in HRR was almost the same in both cribs but it took a longer duration for water to reach the lower layers of the double crib. A spray density of 0.02 gpm/ft^2 (0.82 mm/min) had little effect on the wood crib fire while a gradual reduction in extinguishment time was observed as the density increased from 0.039 gpm/ft^2 (1.59 mm/min) to 0.1 gpm/ft^2 (4.07 mm/min). Overall, a density of 0.2 gpm/ft^2 (8.15 mm/min) or higher was required for rapid crib extinguishment.

Fire Extinguishing Foams -Resistance against Heat Radiation [20]

Author: Henry Persson

The author investigated the resistance of several fire-fighting foams to thermal radiation and ignition inhibition of fuel when covered with a foam layer. Foams of 3% and 6% concentrate as specified by the manufacturers with expansion ratios ranging from 6.5 to 11.5 were used for the tests.

The behavior of a foam layer, when exposed to radiant heating, was investigated in the first test series. The foam was subjected to thermal radiation from a cone radiator in the range of 0-35 kW/m^2 and the drained water was collected in a glass beaker. During each test, the foam disintegration was recorded visually while the evaporation rate and drainage rate were recorded by continuous weight measurements. Similarly, a second series of tests was conducted in the same manner but with a layer of fuel (heptane) in the glass beaker. A small pilot flame was positioned above the foam surface to determine the ignition time of the fuel. The evaporation rate and drainage rate were also determined.

For the third test series, the vapour suppression capability of the foams was investigated. The fuel was placed in a standard reaction flask and then covered with a layer of foam. The flask was sealed and the vapour accumulation above the foam layer was measured using a standard explosiometer. It was reported that for the first two test series, the evaporation rate was almost the same for all the tested foams and proportional to the radiation level, approximately 15 gr/min.kW. This implies that 65 %-75 % of the thermal radiation was used in the evaporation of the foam.

The foam destruction increased exponentially from zero to 0.5-1.5 cm/min at 5 kW/m^2, then steadily to approximately 1.5-2.5 cm/min at 35 kW/m^2. The drainage properties varied considerably among the tested foams with the drainage rate in the range of 1000 to 4000 g/min.m^2 at 35 kW/m^2.

Fire Extinguishing Foams - Test Method for Heat Exposure Characterization [21]

Authors: Sören Isaksson and Henry Persson

The authors built upon the study conducted by Persson [20] on the thermal absorption properties of foams by considering the influence of foam layer thickness and energy balance in the foam-fuel system during heat exposure. The method adopted for the measurement of the drainage rate, foam height and foam destruction rate was improved upon to understand the characteristics of foam in a fire. The foams were subjected to thermal radiation in the ranges of 0-43 kW/m^2.

Visual observation was used to measure the drainage rate between the fuel and the foam solution by having a measuring cylinder beneath the test vessel. The vessel and cylinder were filled with fuel to achieve the desired foam thickness as continuous readings of the foal solution - fuel interface in the cylinder was taken. This technique generated a better and consistent result as compared to utilizing a side drain vessel to determine the drainage rate due to surface tension fluctuation between different fuels and foam types. The drainage characteristics were investigated under six conditions where the drainage vessel and the foam thickness were varied.

Air aspirated foam was placed in a vessel to determine the drainage characteristics for the first series of tests. The vessel was equipped with a plastic hose and tap which was regulated manually during the test. The second test series was similar to the first, but a paper filter was positioned at the bottom to allow the foam solution to pass through. The weight loss for both tests was recorded by a data logging system.

Subsequent modifications were made to the drainage vessel and foam thickness to investigate the free-flowing drainage rate and drainage rate with heat exposure. It was reported that the drainage methods and equipment affected the results to some extent but with slight differences. The 25%, 50% and 75% drainage was collected during the tests as shown in Figure 2.10.

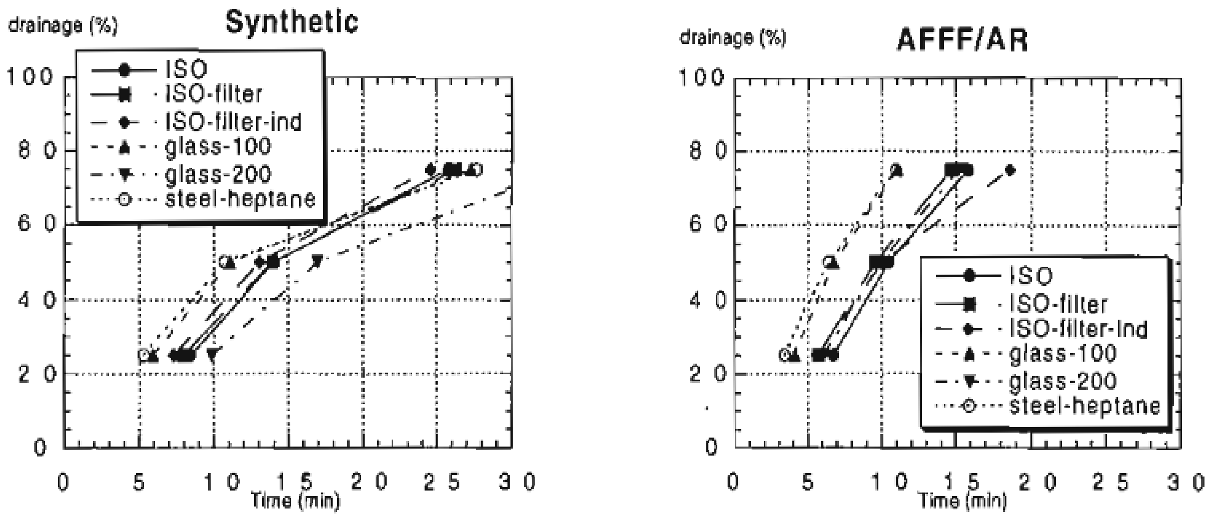


Figure 2.10 - Time to 25%, 50% and 75% drainage as a function of time for all drainage tests [21]

Overall, the technique used to determine the drainage characteristics of foams was improved upon thereby providing a better understanding of foam rheology and heat exposure capability of some fire-fighting foams.

The Performance of Aged Aqueous Foams for Mitigation of Thermal Radiation [22]

Authors: S.A. Magrabi, B.Z. Dlugogorski and G.J. Jameson

In this study, the effect of aging on the performance of aqueous foams as absorbers of thermal radiation was investigated. The author investigated the thermal absorption properties of aged foam and freshly-prepared foam when exposed to radiant heating. The drainage properties such as drainage, evaporation and foam decay rate were compared in relation to the expansion ratio and applied radiant heating.

Heat flux in the ranges of 0-40 kW/m^2 were imposed on the freshly made and aged aqueous foam. A compressed air foam system was used to generate foams with expansion ratios in the range of 5 and 30. 3% foam solution of AFFF foam was used for the tests. The authors represented expansion ratio with letter “E” in their study. The schematic representation of the experimental set up is shown in Figure 2.11

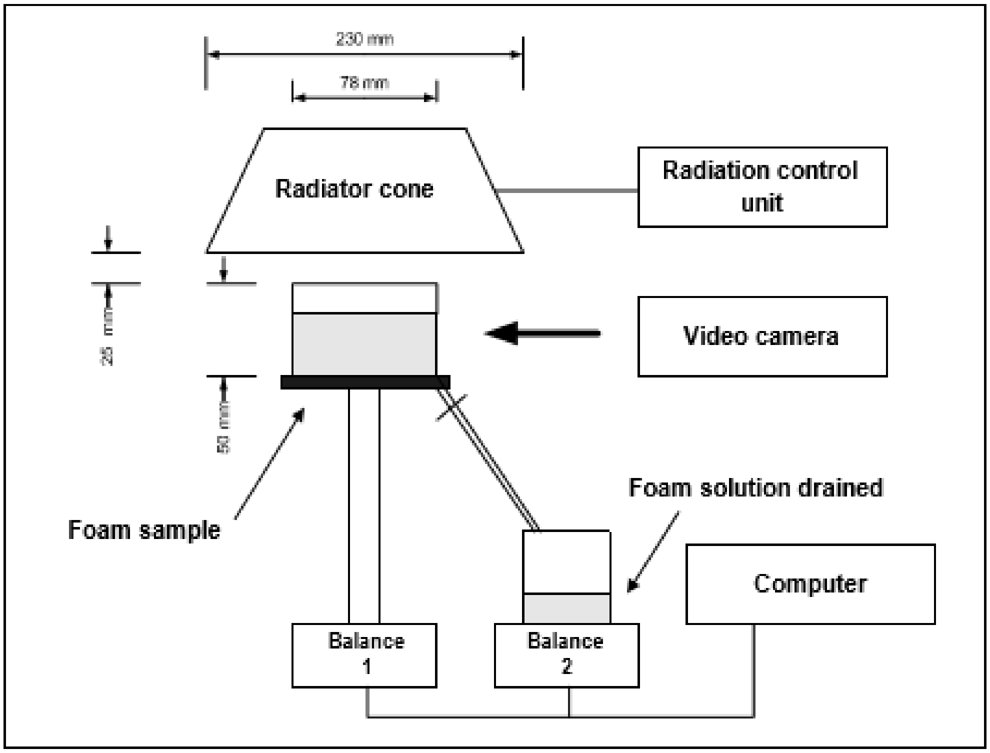


Figure 2.11 - Schematic diagram of the experimental setup for drainage tests [22]

The aging foam was prepared by injecting compressed air into the foam solution to generate low expansion foams E =5,10 and medium expansion foam E =20. The foam was allowed to drain at ambient temperature without radiant heating until it reached an average foam expansion E =30. About 8% of the foam volume changed during the aging process. The drainage characteristics of the aged foam were compared to those of a freshly prepared foam with expansion ratio E =30. E =5 $\longrightarrow$ 30 signifies expansion E =5 foam aged to expansion E =30.

The foam mass and the drained water mass were monitored to determine the effect of aging on foam drainage. The author expressed the drainage rate as normalized drainage rate which represents the ratio of actual drainage rate to the initial foam mass after aging.

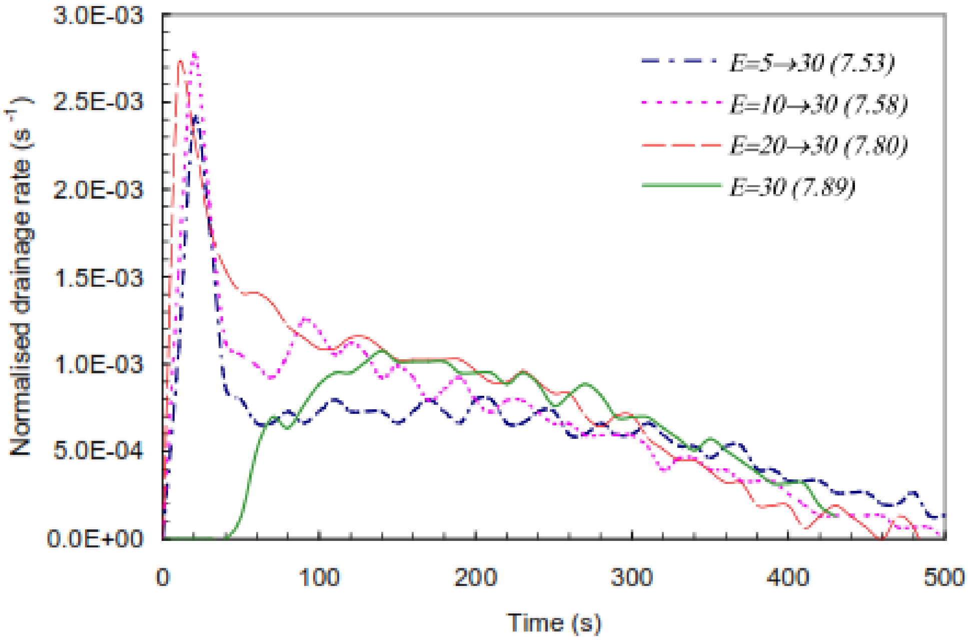


Figure 2.12 - Drainage rate of freshly-prepared foam (E =30) and aged foams

(E =5,10,20 ⟶ 30) at 10 kW/m^2 [22]

It was reported that the foam consistency varied over a prolonged duration of time depending on location. Bubbles were dominant at the top layer of the foam while foam solution was seen at the lower part of the container. The results indicated that the freshly-prepared foam was more stable and drained slower than the aged foam due to a narrower bubble-size distribution. Furthermore, fresh foams required more energy to disintegrate and initiate drainage due to their uniform bubble size distribution. Radiant heating to the bubbles at the top along with the effect of gravitational force to the foam solution at the bottom intensifies the drainage of the foam.

The evaporation rate for the aged foam and fresh foam exhibited a similar pattern when subjected to radiant heating. A linear progression was observed up to 20 kW/m^2 before it rapidly disintegrated. The authors reported that the foam layers collapsed at a rapid drainage rate when exposed to thermal heat fluxes above 20 kW/m^2. Although the authors were unable to conclude whether aging influenced the evaporation rate of the foams, they suggested that the bubble size distribution could be a major contributing factor to investigate in terms of evaporation rate. Hence, further investigation was recommended in this aspect.

The authors superimposed their results on freshly-made foams with the study made by Persson [20] which showed that the experimental data followed a similar trend with high correlation between 5-25 kW/m^2.

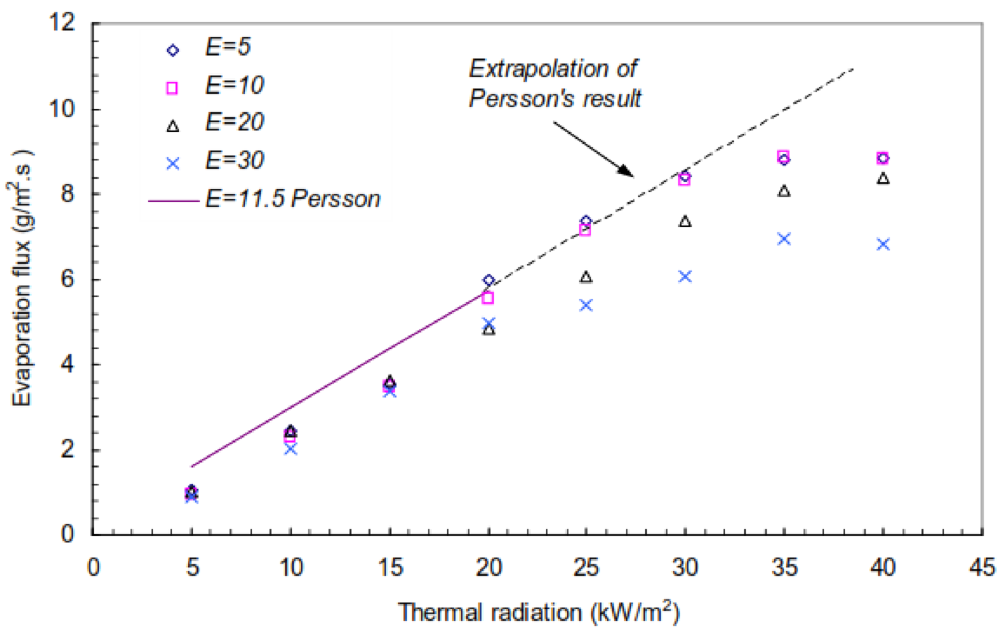


Figure 2.13 - Experimental data on freshly-made foam with the study made by Persson [22]

The aging process on foam disintegration was also investigated with and without radiant heating. The height of the foam decreased from 50 mm to approximately 45-47 mm over a period of an hour without radiant heating. The foam disintegration went through four distinguished stages when subjected to thermal radiation. The thermal expansion of the air bubbles dominated the first stage while rapid loss of liquid occurred afterwards because of evaporation from the foam surface and drainage from the foam bed. The third stage was dominated by evaporation as the drainage rate reduced drastically and remained almost constant. The heating of the sample container gave rise to the boundary effect seen in the fourth stage. The stages are represented as regimes in Figure

2.14. The graph illustrates the effect of radiant heating on the foam decay rate by comparing the foam collapse plots for 10, 20 and 35 kW/m^2. Likewise, the aged foam exhibited a similar pattern under the same operating condition.

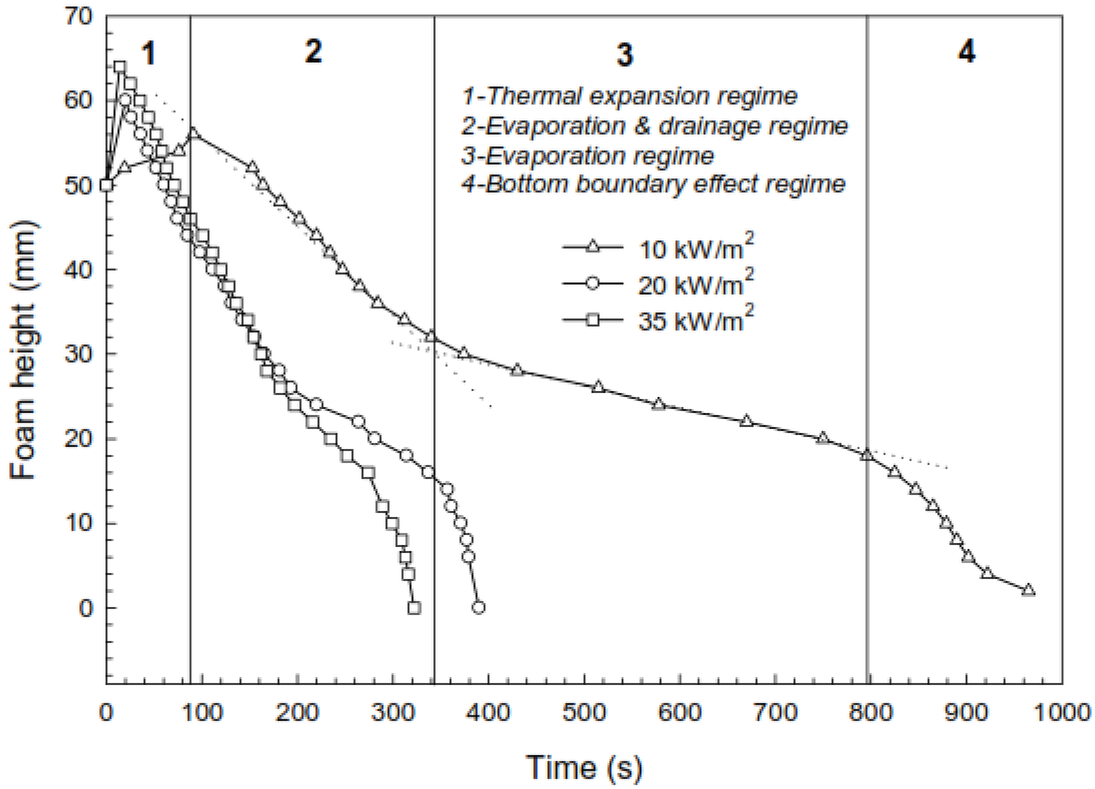


Figure 2.14 - Foam destruction data on freshly-made foam at imposed radiant heating [22]

Overall, it was reported that foam with expansion ratio 1:30 exhibited the most effective thermal absorption among the foams. Therefore, the author concluded that foam with E = 30 is the most cost-effective foam to provide protection against thermal radiation.

In another study, the authors investigated the performance of compressed air foam when exposed to thermal radiation [23]. Aqueous foams in the expansion range 5-30 were subjected to heat fluxes between 0-40 kW/m^2. They applied the principle of half-decay time to evaluate the physical properties of the aqueous foams in response to thermal radiation. The half-decay time was expressed as the time at which the foam height reduced to half its original height. The half-decay time concept indicated that if the same quantity of foam solution is used to generate the foam, the high-expansion foams will provide the longest protection against the effects of thermal radiation. For this study, the freshly prepared foam with expansion ratio of 30 (E = 30) demonstrated the largest decay time due to its superior drainage, evaporation and decay characteristics.

Application of Compressed Air Foam Fire Suppression System [24]

Authors: Andrew K. Kim and George P. Crampton

The National Research Council (NRC) in partnership with the Department of National Defence Canada (DND) investigated the use of a compressed air foam (CAF) fire suppression system to provide fire safety protection to aircrafts and hangar structures. The fire protection objective was to achieve 90% control of the fire in 30 s and extinguishment in 60 s.

Fire suppression tests of the CAF system with three simulated aircraft hangar fire scenarios were conducted to provide technical evidence that the CAF system can provide adequate fire protection, using a combination of overhead CAF nozzles and portable low-level nozzles. The two distribution nozzles used were Turbine Action Rotary and Gear Drive Rotary [25]. The low-level nozzle was positioned near the aircrafts to suppress any fire that could be concealed from the overhead nozzles. The overhead CAF fixed pipe system comprised of three zones namely; air injection zone, development zone and discharge zone. In the first zone, air was injected into a stream of water in such a way that both pressures were balanced. This was achieved by maintaining a steady air and water supply in the pipe. The foam was formed at the second zone when the foam solution with air flows through a segment of flexible tubing. As the foam passes through the hoseline, redistribution of foam was experienced thereby increasing the development of foam. The system can generate uniform foams with expansion ratio ranging from 1:4 to 1:20. A special nozzle was designed to permit smooth discharge of foam at the third zone. Unlike in sprinkler and fixed aspirated nozzles, the CAF nozzles have no sharp bends and no impact points. The CAF system was expected to cover the hangar floor with foam rapidly in other to meet the objective of 30s control or 60s extinguishment.

Two pool fire tests were conducted in a square pan with dimensions of 1.22 m by 1.22 m and in a circular pan of 2.44 m in diameter and lip height of 127 mm. For the small pan test, 8 L of heptane fuel was used floating above 80 mm of water. The fuel was ignited and allowed to burn for 30 s before activating the fire suppression. The nozzle (either overhead or low-level) was activated manually and stayed open until total extinguishment. The fire test results showed that the overhead nozzle CAF system with 0.3% Class A foam controlled (90% fire size reduction) the small pan fire in less than 35 s and extinguished the fire in less than 141 s. The same system with 2% AFFF controlled the fire in less than 55 s and extinguished it in 70 s. Low-level nozzle CAF system with 0.3% Class A foam controlled the small pan fire in less than 28 s and extinguished the fire in less than 56 s. The same system with 2% AFFF controlled the fire in the first 20 s and extinguished it in less than 53 s.

For the large pan test, 40 L of fuel (either gasoline or JP5) was used floating above 100 mm of water in a 2.44 m diameter pan. The pre-burn times for the gasoline fires were 20 to 30 s and 15 to 20 s for the JP5 fires. The fire test results showed that the overhead nozzle CAF system with 0.3% Class A foam controlled the large JP5 pan fire in 180 s and extinguished the fire in 247 s. The same system with 2% AFFF controlled the JP5 fire in 48 s and gasoline fire in 62 s, and extinguished the JP5 fire in 65 s and gasoline fire in 118 s. Low-level nozzle CAF system with 0.3% Class A foam controlled the large JP5 pan fire in 35 s and gasoline fire in 120 s, and extinguished the JP5 fire in 137 s and gasoline fire in 220 s. The same system with 2% AFFF controlled the JP5 fire in 18 s and gasoline fire in 25 s, and extinguished the JP5 fire in 29 s and gasoline fire in 39 s.

For the spill fire tests, 0.9 L/min of heptane was fed through a 12.7 mm diameter pipe and allowed to flow across a sheet of 12.7 mm thick gypsum wallboard placed on the floor. The heptane was ignited and permitted to burn for 15 s before commencing fire suppression. The fire test results showed that the overhead nozzle CAF system with 0.3% Class A foam controlled the spill fire in less than 40 s and extinguished the fire in less than 132 s. Using 2% AFFF, the fire was controlled in 25 s and extinguished in less than 48 s. Low-level nozzle CAF system with 0.3% Class A foam controlled the spill fire in less than 20 s and extinguished the fire in less than 56 s. The same system with 2% AFFF controlled the fire in less than 20 s and extinguished it in less than 53 s. Overall, the test results showed that the CAF system with its overhead and low-level nozzles was able to achieve the fire protection objective in controlling the fire for the three fire scenarios in an aircraft hangar. The use of 2% AFFF solution demonstrated the superiority to 0.3% Class A foam, in both the control and extinguishment of the three test fires. Overhead nozzles alone had difficulty in meeting the control and extinguishment criteria (30 s control and 60 s extinguishment) of the hangar protection, however, the low-level nozzles performed much better and met the control and extinguishment criteria in most of the fire scenarios.

Multipurpose Overhead Compressed Air Foam System and its Fire Suppression Performance [26]

Authors: Andrew K. Kim and Bodgan Z. Dlugogorski

The fire extinguishment capacity of compressed air foam installed in an overhead fixed pipe was studied in this research. The suppression performance of the CAF system on Class A and Class B fires was compared with water mist and sprinkler-based installation.

A mobile test unit measuring 3.5 m x 3.1 m x 3.3 m was used to simulate open space burning with unlimited ventilation for a series of tests and a compartment measuring 6.1 m x 6.1 m x 3.2 m with two window openings of 1.5 m x 1.2 m each was used for the enclosed space burning. A thermocouple tree, containing six thermocouples at 0.3 m intervals, was placed above the center of the fuel with the lowest thermocouple 15 cm above the floor. Likewise, three heat flux meters were placed around the enclosure as shown in Figure 2.15, and another two were positioned 1.7 m away from the centerline of the fuel.

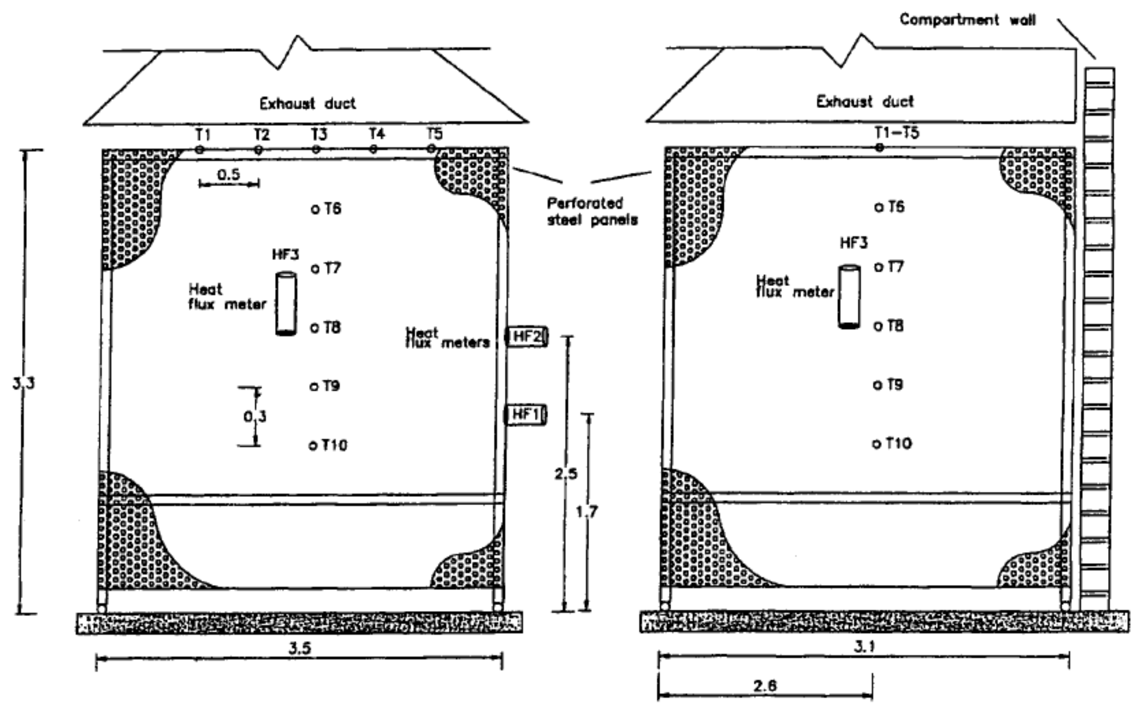


Figure 2.15 - Experimental set-up for compartment fire suppression [26]

Two types of foam were used for the test to investigate the most effective foam concentrate for the fixed CAF system. 0.3% of class A solution and 1-3% of AFFF solution were used to generate compressed air foams of expansion ratios in the range of 4 and 10. It was observed that the Class A foam extinguished the heptane pool fire quicker than the Class B foam due to its wetting properties. However, the former required a large amount of water as compared to the Class B foam.

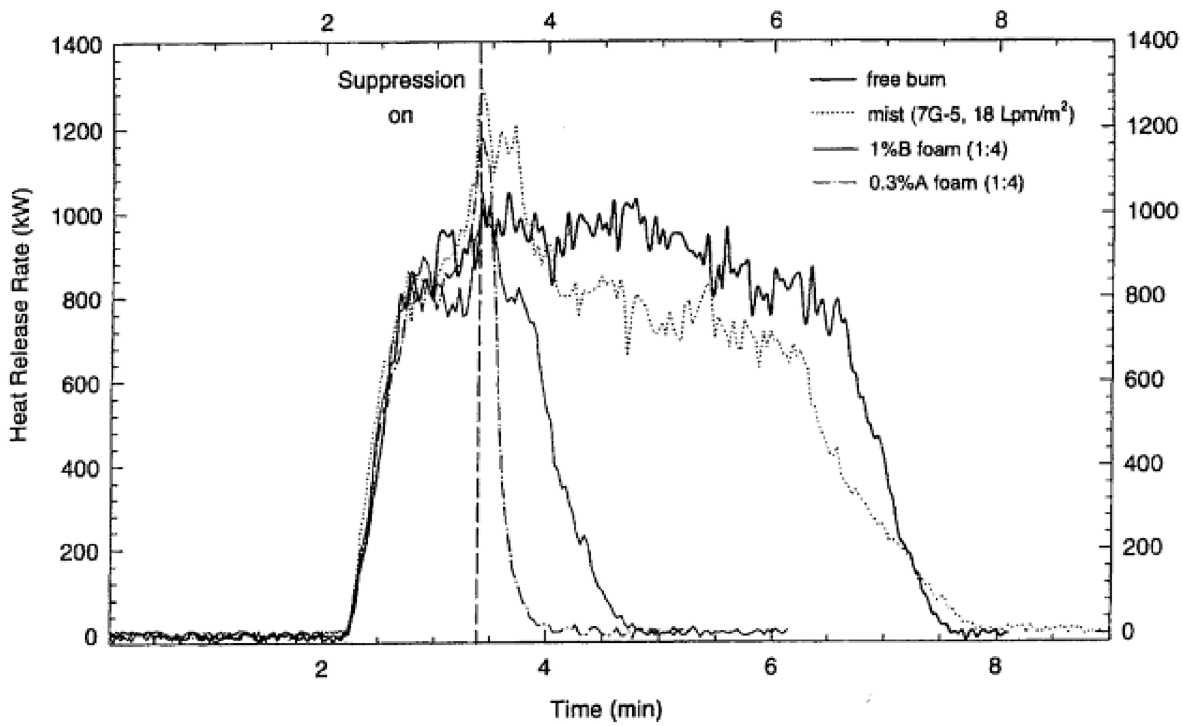


Figure 2.16 - Suppression Effectiveness of CAF system and Water Mist on Heptane Pool Fires (Single Nozzle) [26]

Figure 2.16 illustrates the suppression performance of 0.3% Class A foam, 1% Class B foam and the water mist system on heptane pool fires using a single nozzle system. The generated foam from the CAF system forms a foam blanket on the surface of the liquid pool fire. This hinders the heat transfer from the flame to the fuel surface and reduces the vaporization of the fuel. A rapid decline was observed in the heat release rate immediately after the CAF system was activated in contrast to a gradually decrease initiated by the mist system. The plummeted temperature by the CAF system represents a quick knockdown, control and extinguishment of the fire. 0.3% Class A foam extinguished the fire quicker than the 1% Class B foam while the water mist was unable to effectively extinguish the pool fire.

The extinguishing capability of the systems on two sizes of wood cribs was also investigated. Both sizes were constructed of pine sticks with dimensions of 40 mm by 40 mm by 0.6 m long. Each stack had outside dimensions of 0.6 m by 0.6 m. The first wood crib comprised of 5 layers of pine sticks with a height of 0.3 m high and the second size comprised of 10 layers of pine sticks.

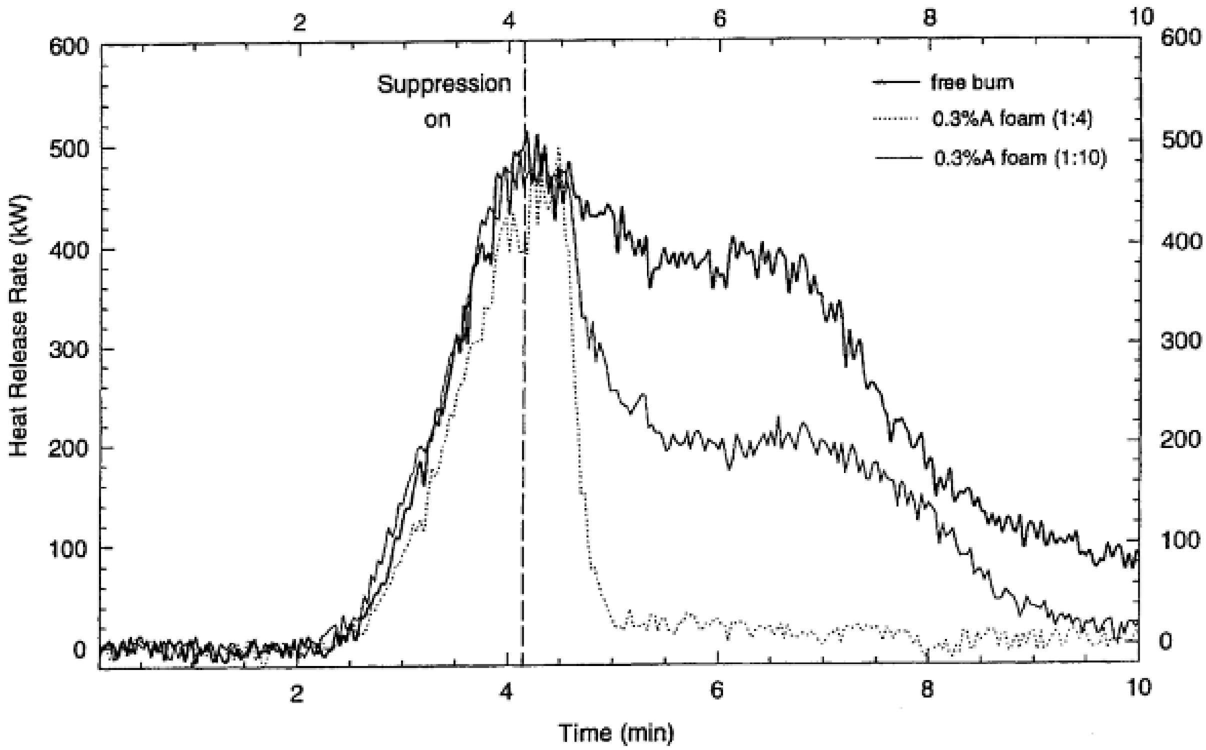


Figure 2.17 - Suppression Effectiveness of CAF system and Water Mist on the Wood Crib Fires (Single Nozzle) [26]

Figure 2.17 depicts the free burning of the wood crib fire and CAF suppression by 0.3 % Class A foam with expansion ratio1:4 and 1:10 from a single nozzle above 5 layers of the wood crib fire. A sharp drop was observed when foam with expansion ratio 1:4 was applied. The fire was controlled in less than 1 min and eventually extinguished at 3 min 10 secs whereas the foam with expansion ratio 1:10 reduced the fire size but required more than 5 mins for complete extinguishment. The foam with expansion ratio of 1:4 was more effective on the wood crib fire than the expansion ratio with 1:10 because of the higher water content, which was able to stick to the surface of the wood. For the bigger wood crib fire, the CAF system covered the burning surface with a foam blanket within 1 min of activation. However, there was a persistent flame within the core of the wood crib for 6 min indicating the possibility of re-ignition

Overall, the CAF system demonstrated a superior fire suppression capacity than the water mist installation on wood crib fires and flammable liquid pool fires in an open space. Both systems exhibited similar extinguishing capacity on flammable pool fires in an enclosed space. Furthermore, the CAF system performed much better on large wood crib fires than the sprinkler system

Evaluation of the Fire Suppression Effectiveness of Manually Applied Compressed Air Foam System [27]

Authors: Andrew K. Kim and George P. Crampton

In this research, the performance of a mobile CAF system in suppressing fully developed compartment fires was evaluated. The suppression performance of the manually applied CAF system on full-scale compartment fire tests was compared to the traditional hose stream application of water alone and water-foam solution under similar conditions.

Two compartment units of 4.26 m by 3.65 m with 2.44 m ceiling height were joined with a hallway 3.65 m long to simulate a real residential compartment or office space arrangement. There were several ventilation openings in the rooms as shown in Figure 2.18 for sufficient supply of fresh air. The fire load comprised of two wood cribs, a mock-up sofa, and Oriented Strand Board (OSB). Each wood crib was constructed with 48 pieces of 0.038 m x 0.09 m x 0.8 m pine studs, which could generate a 1 MW fire. Two digital video cameras were set up outside the test compartment to obtain visual records.

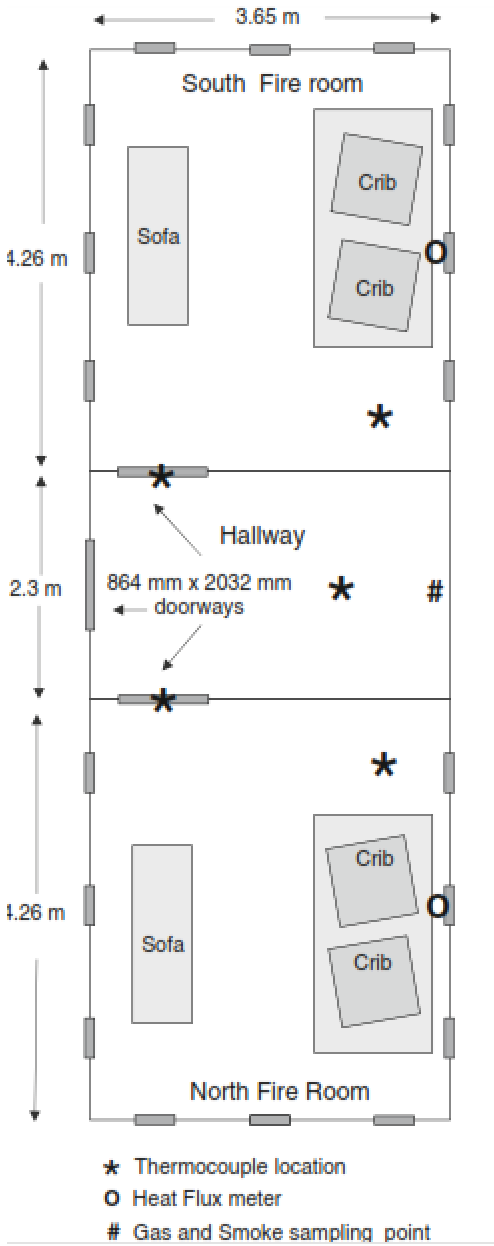


Figure 2.18 - Plan view of test room [27]

A total of 10 full scale fire suppression tests were conducted in the test compartment using a CAF system, hose stream application of water or foam solution. The results of the experiments are shown in Table 2.3 indicating the knockdown time, water flow rate and total water consumption of the three suppression systems

Table 2.3 - Result of Fire Suppression Test [27]

Test #	Description	Foam concentration	Fire room	Water flow rate	Knock-down time	Water used for knock-down	Total water consumption
1[a]	CAF	0.5%	North	250 L/min (66 GPM)	46 s	<151 L (40 US gal)	159 L (42 US gal)
2[a]	Water only	0	South	360 L/min (95 GPM)	32 s	<132 L (35 US gal)	170 L (45 US gal)
3[a]	CAF	0.5%	South	182 L/min (48 GPM)	90 s	<284 L (75 US gal)	367 L (97 US gal)
4[a]	CAF	0.5%	North	189 L/min (50 GPM)	76 s	<246 L (65 US gal)	265 L (70 US gal)
5	Water only	0	North	360 L/min (95 GPM)	35 s	148 L (39 US gal)	151 L (40 US gal)
6	Water only	0	South	360 L/min (95 GPM)	40 s	87 L (23 US gal)	95 L (25 US gal)
7	Foam-solution	0.5%	South	360 L/min (95 GPM)	32 s	53 L (14 US gal)	238 L (63 US gal)
8	Foam-solution	0.3%	North	360 L/min (95 GPM)	13 s	57 L (15 US gal)	96 L (25 US gal)
9	CAF	0.3%	North	95 L/min (25 GPM)	15 s	23 L (6 US gal)	91 L (24 US gal)
10	CAF	0.3%	South	95 L/min (25 GPM)	15 s	23 L (6 US gal)	87 L (23 US gal)

The first four results were not used because the system was not properly calibrated. In the subsequent tests, the CAF system required a lower water flow rate to suppress a compartment fire as compared to water only or foam-water solution. A CAF system with a 95 L/min water flow rate suppressed the test fire better than the hose-stream application with water only or with foam-solution using 360 L/min (95 GPM).

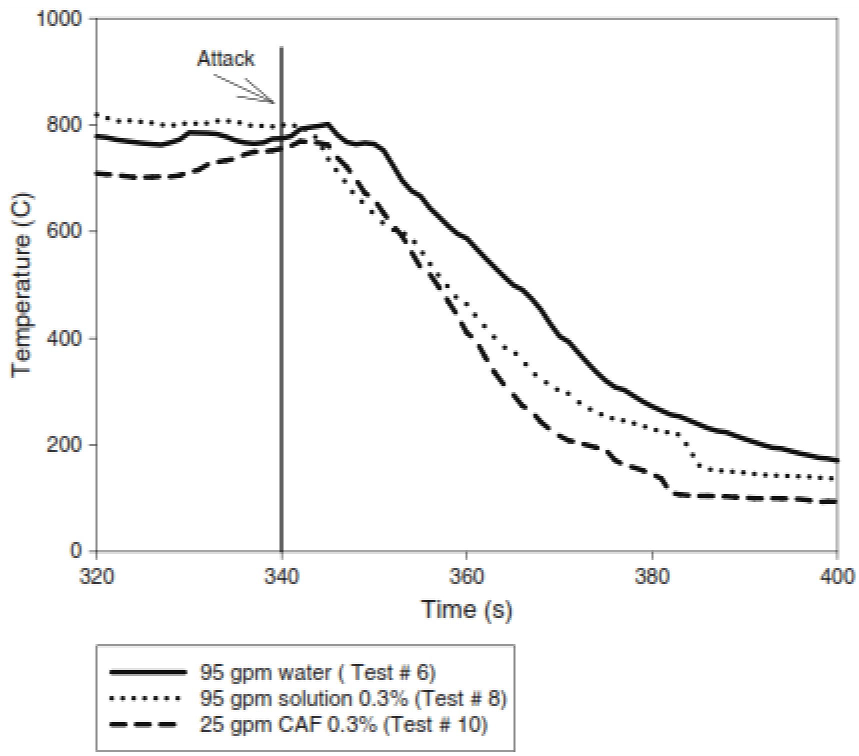


Figure 2.19 - Average temperature in the fire room (Test #6, #8 and #10) [27]

Figure 2.19 shows the average temperatures in the fire compartment for Test #6, #8 and #10. Test #6 was with water only, Test #8 was with foam-water solution while Test #10 was with CAF system. The graph illustrates that at the point of fire suppression by fire fighters, the average temperature in the fire room was almost equal in the three tests. However, after the fire suppression, there was a rapid drop in the average room temperature with the CAF system than with water alone or with foam-water solution. The knock-down time to drop the average room temperature to the critical temperature of 200ºC when the CAF was used (in Test #10) was 35 s as compared to 45 s for the foam-water solution (in Test #8) and 60 s for water alone (in Test #6).

Compressed Air Foam (CAF) Fire Suppression System for Aircraft Hangar Protection [28]

Authors: Andrew K. Kim and George P. Crampton

In this research, the National Research Council (NRC) investigated the feasibility of using a fixed pipe compressed air foam system to provide fire safety protection to aircrafts and hangar structures. The minimum requirements for the various parameters of the CAF system to meet the fire protection objective and highlight the benefits of the CAF system over existing sprinkler systems were investigated. Likewise, the fire suppression performance of the developed fixed pipe CAF system and foam-water sprinkler system were compared in this study.

A full-scale fire test set-up for foam-water sprinkler and CAF systems was constructed. The test set-up included a 3.74 m by 3.74 m test piping grid for the foam-water sprinkler and CAF systems. There were four sprinkler heads, or four CAF nozzles installed at each corner of the piping grid. The piping grid and the sprinkler heads and CAF nozzles were installed 4.5 m or 7.6 m above the floor. The sprinkler heads used in the tests were Viking Standard Response Model M Pendant, Standard Orifice, 15 mm BSP Identification VK102 K-Factor: 5.6. Each sprinkler was designed to cover approximately a 6 m (20 feet) diameter circular area. The small spinner CAF nozzle had a 25.4 mm diameter body with a 19.05 mm outlet opening piece attached to the body. The outlet opening piece spins due to the momentum of the CAF flow as it discharges CAF. This spinning action distributes CAF uniformly over a 5.27 m diameter area. This nozzle was used in the tests with a flow rate of approximately 23 L/min.

The test fire was a heptane pool fire. Commercial grade heptane fuel in a fire test pan was placed on the floor, centered below the piping grid for the sprinkler and small rotary nozzle CAF tests. The fire test pan was square, straight-sided, with an area of 4.65 m^2, and made of 6.4 mm thick steel plate. The test pan contained not less than a 25.4 mm deep water layer, with approximately

100 to 205 litres of heptane poured over the water. The water depth was adjusted to provide a distance from the top of the pan to the surface of the heptane fuel of not less than 203 mm.

Foam concentrates used in the tests comprised of both Class A and Class B foam concentrates. The Class A foam concentrate was used only in the CAF tests, at approximately 1% while 3% of Class B foam concentrate was used in the sprinkler tests and approximately 2% in the CAF tests. The experimental procedure used for the study was in accordance to the requirements listed in UL162 standard [29].

Table 2.4 - Results of Pool fire test [28]

Test #	1	2	3	4	5	6	7	8
System	Foam-water sprinkler	CAF	CAF	CAF	CAF	Foam-water sprinkler	CAF	CAF
Nozzle height (m)	4.5	4.5	4.5	4.5	4.5	7.6	7.6	7.6
Water flow rate (L/min)	227	90	90	90	90	227	90.8	90.8
Air flow rate (L/min)	N/A	905	905	905	905	N/A	939	939
Foam type	Class B (National)	Class B (National)	Class A (Silvex)	Class B (National)	Class A (Silvex)	Class B	Class B (National)	Class A (Silvex)
Foam conc. % (%)	3	2	1	2	1	3	2	1
Expansion ratio	3.5	10	10	10.9	8.62	3.5	10	10
Drainage time (min:s)	-	3 : 30	10 : 00	3 : 30	10 : 00	-	3 : 30	10 : 00
Extinguishment time (min:s)	2 : 32	0 : 50	0 : 59	0 : 49	1 : 06	2 : 16	0 : 50	1 : 09
Burn-back time (min:s)	9 : 00	23 : 35	10 : 10	21 : 15	9 : 15	9 : 21	23 : 40	9 : 37

A series of suppression tests was conducted on a large heptane pool fire using the fixed pipe system and the foam-water sprinkler system. The results of the experiments are shown in Table 2.4 indicating the water flow rate, extinguishment time, drainage time and burn-back time. A low expansion ratio of 3.5 was used for the foam-water sprinkler system while much higher expansion ratios of 8.5 and 10 were used for the CAF system. For the first series of tests, the nozzle height for both systems was 4.5 m about the fire at which the suppression capability of both systems was evaluated. The extinguishment times for the CAF system for four consecutive tests were less than a minute as compared to the extinguishment time of 2 mins 32 s for the foam-water sprinkler system, with much less water flow rate. This shows that the CAF system extinguished the fire in less than half the time of the second system. Furthermore, the burn-back time for the CAF system using Class B concentrate was more than double the burn-back time of the foam-water sprinkler system. However, the burn-back time for the Class A CAF system was slightly higher than the burn-back time of the foam-water sprinkler system.

The nozzle was positioned at 7.6 m above the pool fire for the second test series and the expansion ratio for both systems remained the same. Foam concentrates of 3 % for foam-water sprinkler system, 2 % for Class B CAF system and 1 % for Class A CAF system were used. A similar trend as the first series of tests was observed as the extinguishment time for the foam-water sprinkler system was 2 mins 16 s, which exceeded twice the time for both CAF systems. Likewise, the burn-back time for the Class B CAF system was twice the burn-back time of the foam-water sprinkler system.

Overall, the results showed the superior suppression performance of the fixed pipe CAF system over the foam water sprinkler system. Also, the CAF system exceeded the minimum fire extinguishment and burn-back thresholds required by UL-162 using both the Class B and Class A foams.

Use of Compressed Air Foam Technology to Provide Fire Protection for Power Transformers [30]

Authors: Andrew K. Kim and George P. Crampton

The authors investigated the fire suppression performance of a compressed air foam system for the protection of power transformers. Current fire protection systems for power transformers using sprinklers require a large quantity if water, which may cause a problem to their electrical conductivity as well as creating water damage and negative environmental impacts. Another potential challenge is the clean-up process after fire suppression. This might delay the re-start of the power transformers and prolong the power shutdown to the community.

Full scale fire tests were conducted to determine the fire suppression capability of the CAF system and compared with water deluge system for protection of power transformers. A mock-up power transformer was simulated for the experimental study using the worst fire scenario of an explosion in which oil from the transformer generated fire hazards on the top, bottom centre and sides of the mock-up. Four thermocouples were installed on the power transformer mock-up and heat flux meters were used to determine the radiation fluxes from the set-up. Two video cameras were strategically positioned for visual observation during the test.

A CAF distribution system with large Flow Gear Driven Rotary (GDR) nozzle and small Flow Turbine Action Rotary (TAR) nozzle were strategically positioned around the power transformer for the tests as shown in Figure 2.20.

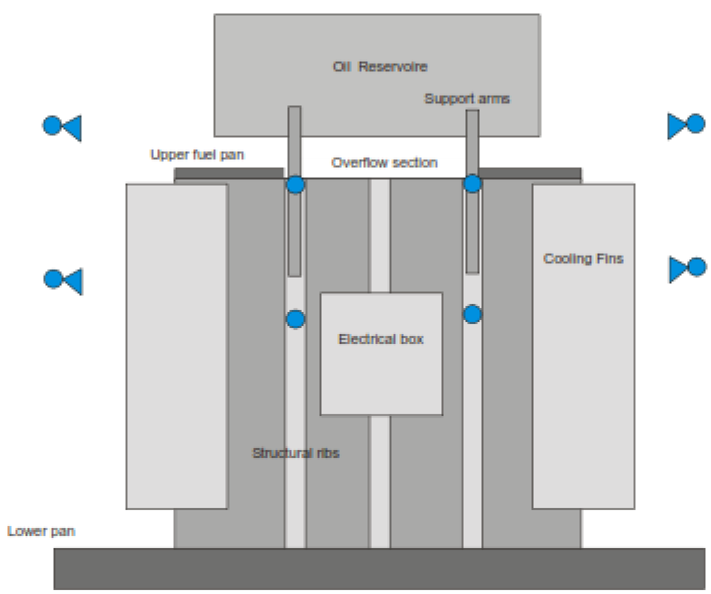


Figure 2.20 - Location of the CAF Nozzles [30]

A series of suppression tests was conducted on the mock-up power transformer, using the CAF system and water deluge system. The results of the tests are shown below in Table 2.5, indicating the nozzle type, pre-burn time, application time to suppress and extinguish.

Table 2.5 - Results of Power Transformer Test [30]

Test #	1	2	3	4	5	6
Description	Deluge	CAF	CAF	CAF	CAF	CAF
Nozzle type	sprinkler	TAR	TAR	TAR	GDR	TAR
# of Nozzles	21	4	3	3	2	8
Foam Type	none	Class A	Class A	Class B	Class B	Class B
Foam Concent. (%)	none	1	1	2	2	2
Flow Rate (L/min)	910	88	66	66	160	160
Pre-heat (ºC)	75	76.5	76	77	75	75
Pre-burn time (min:s)	1:20	1:21	1:27	2:26	1:25	1:15
Application time to suppress (min:s)	2:05	1:09	2:16	1:21	1:33	1:13
Application time to extinguish (min:s)	3:53	1:24*	4:02	2:54	1:58	1:29

* pan on the side did not receive foam and was left burning

The water deluge system with 21 spray nozzles was able to extinguish the test fire in 3 min 53 s at a flow rate of 910 L/min. The two Class A CAF systems with 1% foam concentration used less flow rate to extinguish the fire at 1 min 24 s and 4 min 2 s. The difference between the suppression times was due to the positioning of the nozzle. Figure 2.21 shows the fire suppression capacity of the water deluge system as compared to the CAF system with a significant decrease in the temperature after the activation the CAF system.

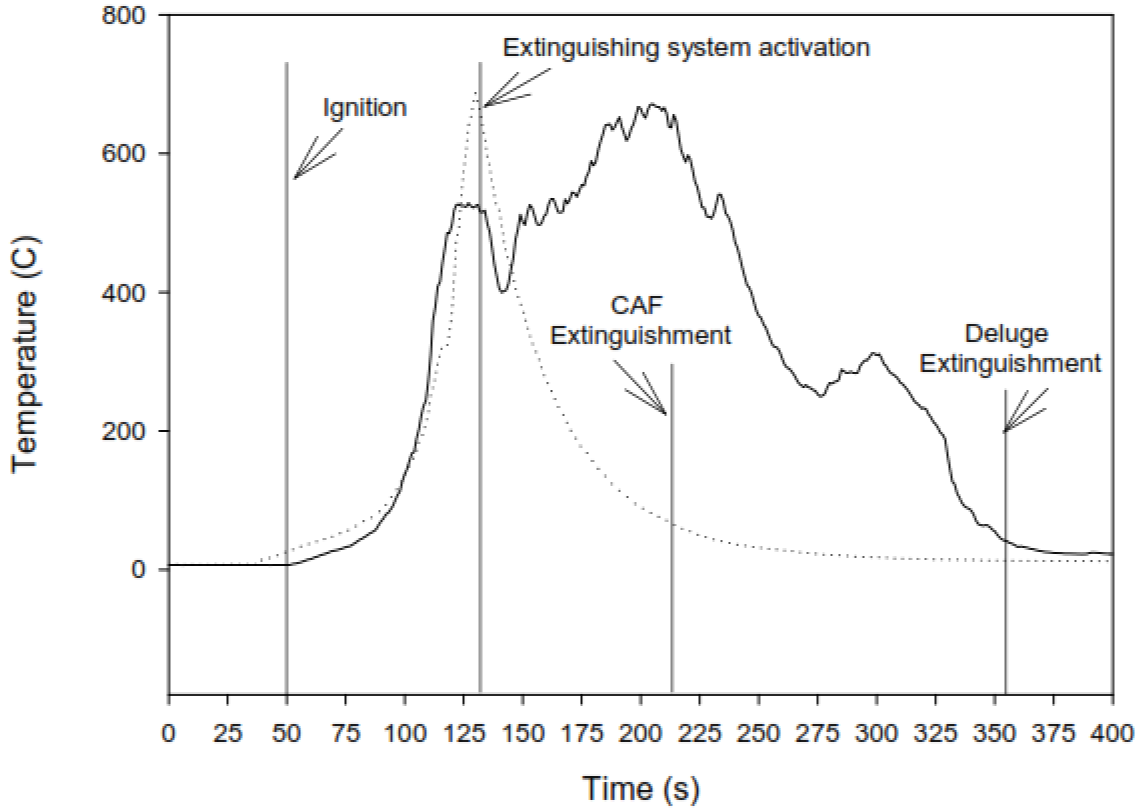


Figure 2.21 - Extinguishment time for both CAF system and water deluge system [30]

The results show that the CAF system, either with 2 large GDR nozzles or with 3 or 4 small TAR nozzles, performed much better than the water deluge system with 21 sprinkler heads. The CAF system with 3 TAR nozzles using 1 % Class A foam concentrate extinguished the test fire in 4 min 2 s, which is almost the same as the results of the water deluge system. However, the 3 TAR CAF system used less than 8% of the total water flow rate of the water deluge system.

The CAF system with 2 GDR nozzles using 2 % Class B foam concentrate extinguished the test fire in 1 min 58 s, which is almost one half of the extinguishment time of the water deluge system. And, the water usage was less than 18 % of the total flow rate of the water deluge system. The CAF system with 8 TAR nozzles using 2 % Class B foam concentrate extinguished the test fire in 1 min 29 s, with far less water requirement than the water deluge system.

Overall, the study shows that a CAF system can provide the required fire protection for power transformers, more effectively with much less water requirement, compared to a traditional water deluge system.

The use of small-scale test data to characterize some aspects of fire fighting foam for suppression modeling [31]

Authors: Brian Y. Lattimer, Christopher P. Hanauska, Joseph L. Scheffey and Frederick W. Williams

The drainage characteristics of aqueous foam at low expansion ratios were investigated under several experimental conditions. The tested aqueous foam was MIL-SPEC 6 % AFFF at low expansion ratios of 3-10. The foam was subjected to constant radiant heating in the ranges of 0-50 kW/m^2. Experimental variables such as expansion ratio, irradiance level, initial foam thickness, fuel beneath the foam and initial fuel temperature were considered to evaluate the foam evaporation rate, solution drain rate and fuel ignition time.

A small-scale test apparatus was developed to quantify the foam mass losses due to evaporation and drainage when exposed to constant radiant heating. The test set-up consisted of a test pan, a solenoid valve, a drain collection container, two load cells, thermocouples, a total heat flux gauge, a radiant heater and a pilot flame. The test pan was cylindrical in shape with dimensions of 230 mm in diameter, 150 mm high and thickness of 1 mm. The test pan was made of stainless steel. The mass of the foam in the test pan was continuously monitored using a load cell. As shown in Figure 2.22, the bottom of the test pan was slightly tapered to guide the drained solution toward the center of the pan. At the center of the pan, there was a 53 mm diameter opening that allowed the drained solution to flow out of the test pan into a transparent secondary vessel.

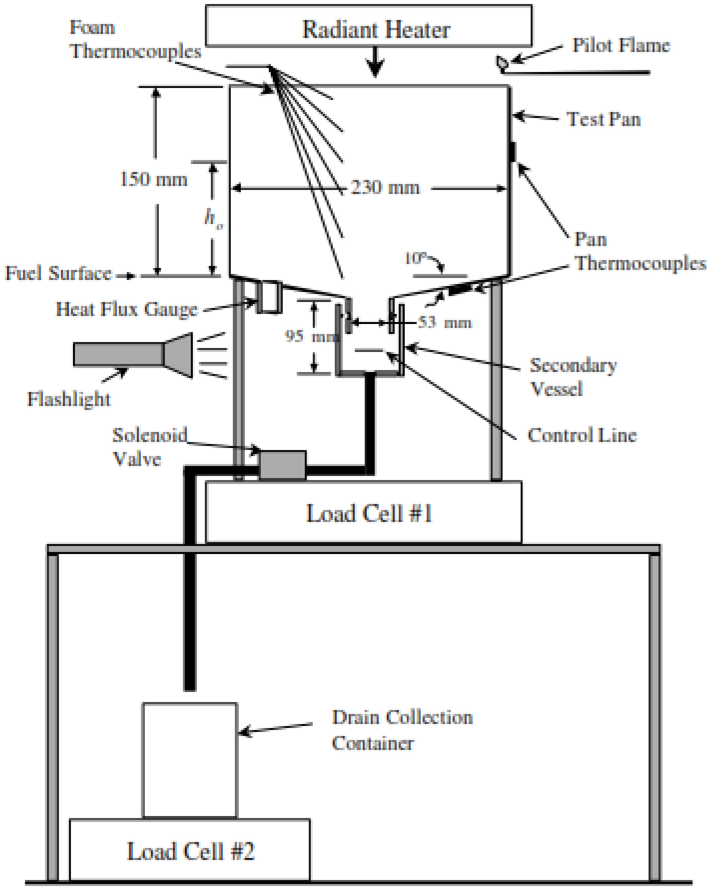


Figure 2.22 - Experimental Set-up [31]

The first test series was conducted without radiant heat to validate the experimental approach. Since no heat was applied, there was no loss due to evaporation while the foam mass reduced due to bubble disintegration and water runoff from beneath as shown in Figure 2.23. Rapid loss of foam mass was observed as the solution drained out of the foam bed during the first few hundred seconds. The drainage rate gradually reduced as the foam became drier. Overall, the foam mass and appearance disintegrated mass very slowly with time. The test was conducted at room temperature using foam with expansion ratio of 6. The author denoted expansion ratio as ER.

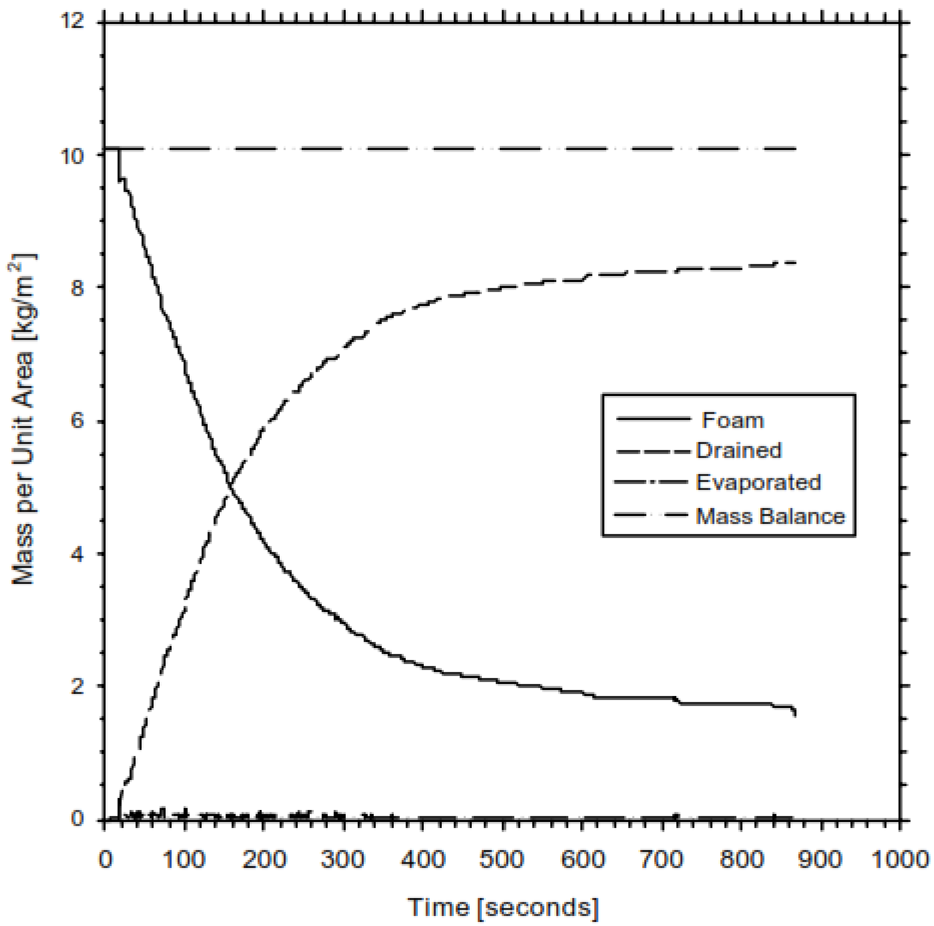
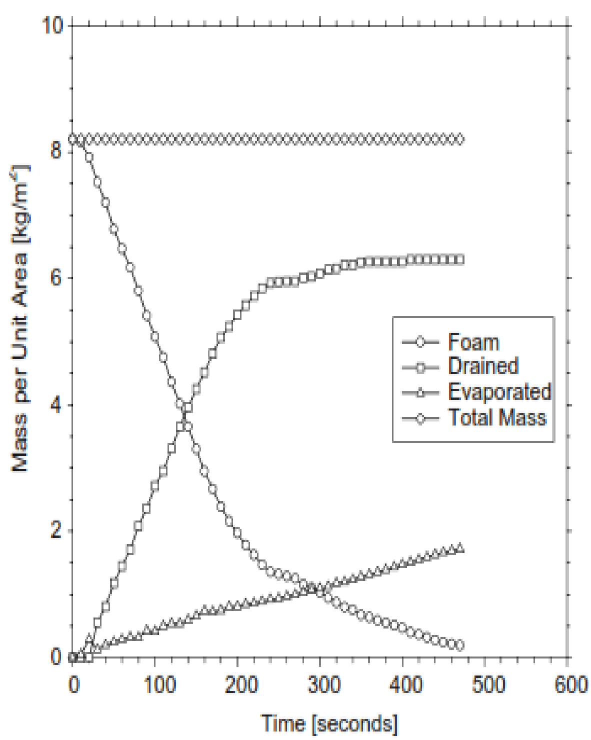


Figure 2.23 - Mass loss of foam with ER=6 due to no thermal radiation. [31]

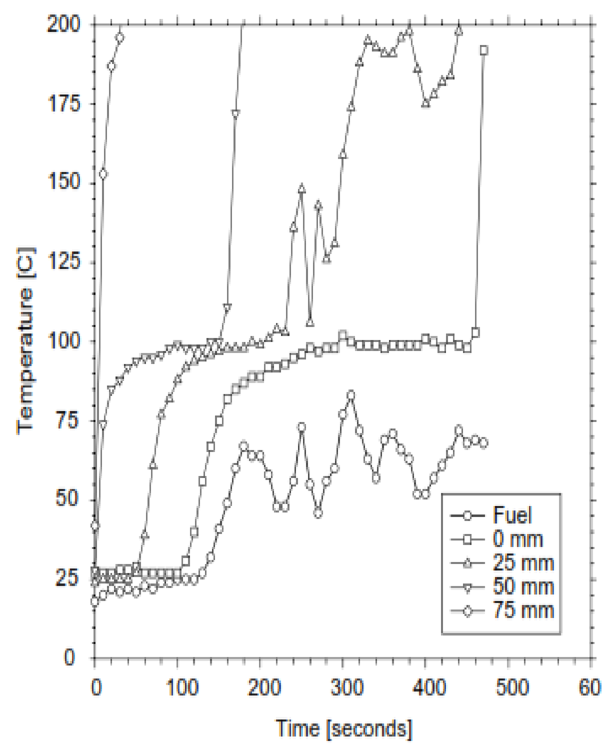
Foams with expansion ratios of 3, 6 and 10 were exposed to thermal radiation of 20, 35 and 50 kW/m^2. It was reported that the foam with ER= 3 drained faster than the foam with ER= 6. After an initial rapid drainage rate, the drain rate level for both expansion ratios became similar. Mass losses for foams involving heat exposure were due to solution draining from the foam bed and foam evaporation. It was observed that as the irradiance level increased, the amount of foam evaporation increased causing the foam mass to be depleted in a shorter period of time. Likewise, the fuel ignition time was shorter with an increase in irradiance. However, the foam mass loss with time was similar for all irradiance levels.

The foam height had a significant impact on the drained solution but little effect on the evaporation rate. Taking into account the variation in the irradiance with depth in the pan, the evaporation rate of the foam was unaffected by the foam height. However, foams with higher expansion ratios had higher peak drain rates at the beginning of the test. This occurred for longer periods before decaying. The result was similar to the study conducted by Persson et al [20]

Figure 2.24 (i-iii) shows the mass loss of foam with ER=6 when exposed to radiant heating of 20 kW/m^2. The heat was applied on a 50 mm thick foam layer which was placed over a layer of JP-5 fuel.



(i)



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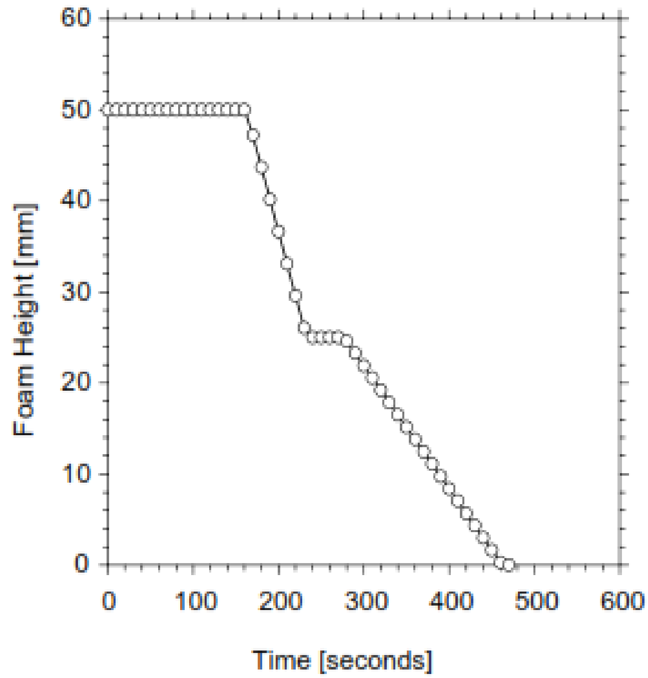

(iii)

Figure 2.24 (i-iii) - Mass loss of foam with ER=6 due to radiant heating of 20 kW/m^2 [31]

It was reported that during the first 100 s, the foam expanded, and the bubble began to collapse. At 150 s, the temperature above the fuel surface rapidly increased to above 100ºC indicating that the foam blanket had been reduced to less than 50 mm. However, there was no change in the temperature at the bottom of the foam blanket. A reduction in the foam height was observed and the temperature at the lower part of the foam and fuel began to rise during the next 100 s. After approximately 250 s, the foam thickness was about 25 mm. At 300 s, most of the solution drainage had ceased and the foam had the appearance of a boiling mixture with bubbles expanding and bursting at a rapid rate. The foam continued to behave in this manner until the foam blanket was almost completely depleted at approximately 470 s. Shortly after this, the fuel layer was ignited. The ignition time was 575 ±5 s in all tests.

2.9 Summary of the review of compressed air foam system

Many studies had been conducted to investigate the drainage characteristics of fire-fighting foams. The foam mass loss rate and thermal absorption properties of fire-fighting foams were studied by several researchers and reported in different papers [20-23] [31]. The authors implemented different methods to quantify the evaporation rate, drainage rate and fuel ignition time of foams in relation to variable experimental conditions. Some of the experimental set-up could only measure foam losses with only foam in the pan [20] [22] while others investigated the ignition time of fuels placed underneath the foam [21] [31]. In all the papers, the tested foams had expansion ratios in the ranges of 3-30 and were subjected to thermal radiation of 0-50 kW/m^2.

Overall, the drainage rate of foams with lower expansion ratio was faster than that of foams with higher expansion ratio. The foam evaporation rate increased as the irradiance level increased which in turn reduced the foam depletion time and fuel ignition time. However, the foams exhibited similar thermal-absorption properties when exposed to heat.

The extinguishing performances of compressed air foam system on different platforms were studied and reported in different papers [24-28] [30]. The suppression capability of CAF system on pool fires and wood crib fires was compared to other extinguishing agents. It was reported that the CAF system demonstrated superior extinguishing performance than water mist and sprinkler installation on wood crib fires and flammable liquid pool fires [26]. Foams with low expansion ratios were more effective on wood crib fires than higher ratios as it was able to adhere to the burning surface. The CAF system was more economical in suppressing pool fires as it only required small amounts of water and foam concentrate to extinguish the fire.

Furthermore, it was found that a mobile CAF system possessed quicker fire knock-down qualities than the application of water and water-foam solution for the suppression of fully developed compartment fires [27].

3 MATERIALS AND METHODOLOGY

This chapter gives a brief description of the portable compressed air foam system developed for this research and its components and presents the procedures used for the discharge range test, flow rate test, fire suppression test and drainage test.

3.1 Materials and Apparatus

3.1.1 Foam Concentrate

The foam concentrate used for the tests was Alcohol-Resistant Aqueous Film Forming Foam (AR-AFFF). The concentrate was recommended by the manufacturer for use at 3 % for hydrocarbon fuels and 6 % for polar solvent fuels. It was manufactured by Angus (see Fig 3.1). The AR-AFFF foam concentrate was selected for the test because of its superior firefighting properties over other types of concentrate (see Table 2.1 for details).

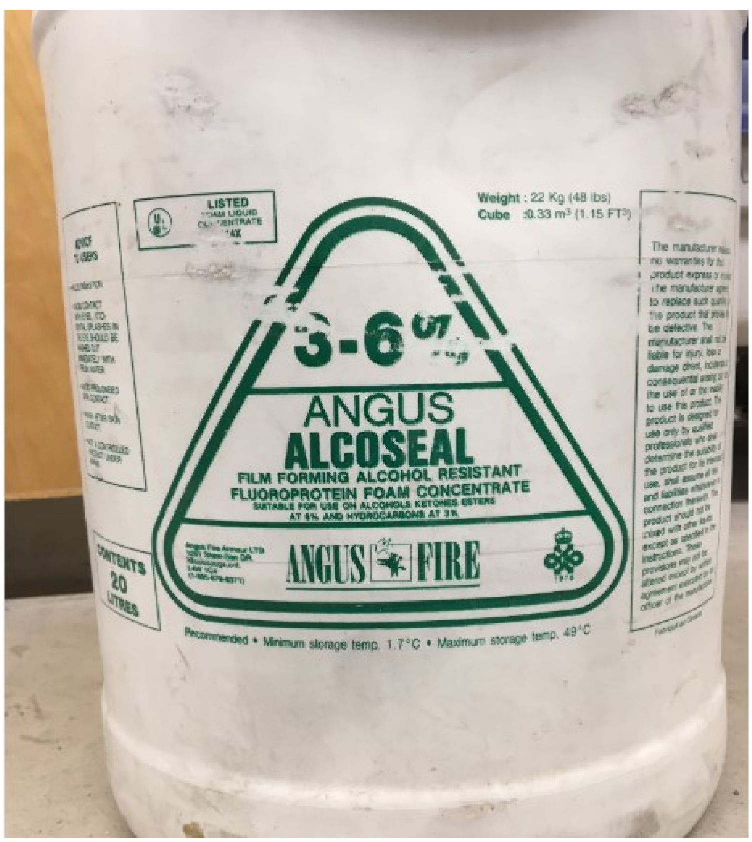

Figure 3.1 - AR-AFFF foam concentrate

3.1.2 Foam Generator

The foam generator comprised of a pressurized container, control valve and air intake. The foam generator was used in connection with an air compressor and nozzle to generate compressed air foam. The pressurized container had a capacity of 3 L.

Figure 3.2 - Foam Generator

The CAF generating system operates by injecting air under pressure into the tank, containing the premixed solution, which in turn produces an upward thrust of the solution stream through a throat to the hoseline. The throat has a calibrated orifice that dictates the percentage of air in the compressed air foam. A schematic diagram of the CAF generating system is shown in Figure 3.3.

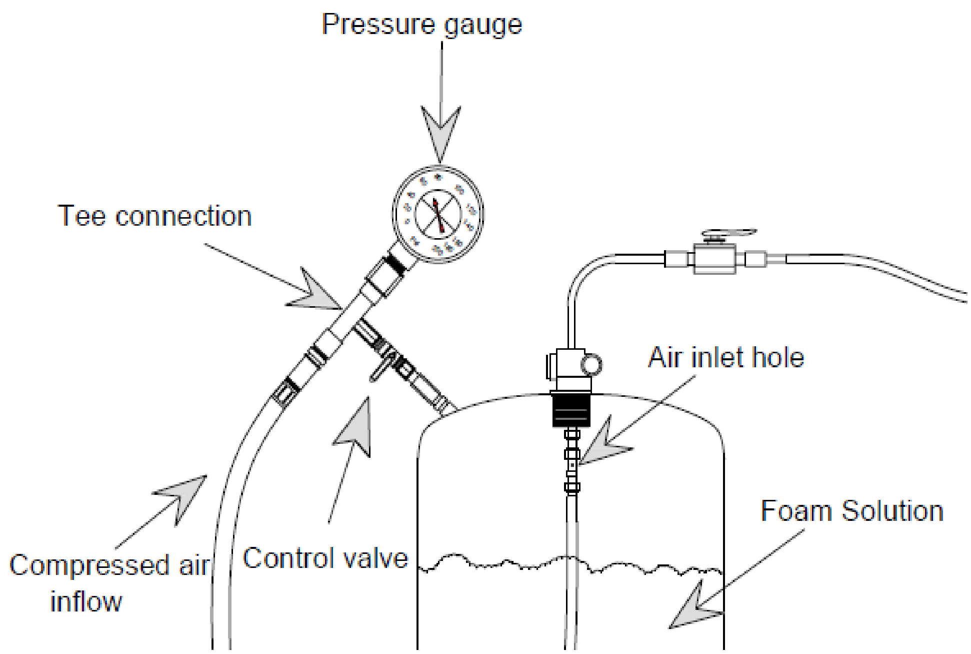

Figure 3.3 - Schematic diagram of the CAF generating system

3.1.3 Nozzle: Gun and Tube

The type of nozzle used determines the spread and discharge range of the generated foam. Also, it is essential for quick fire suppression. The tube was used to investigate the discharge range and flow rate of the generated foam while the nozzle gun was used for the fire test. The tube was mounted on a stand for the discharge range test and foam flow rate test.

Figure 3.4 - Gun and Tube Nozzle

3.1.4 Scale

A Taylor series high capacity glass scale was used to measure the weight of the expanded foam and to calculate the expansion ratio. The scale had a capacity of 13.6 kg with an accuracy of 0.5 g through the entire scale range. The scale has the ability to set zero weight with an empty container (tare) and to display the net weight.

3.1.5 Measuring Container

Calibrated containers were used to determine the quantity of water required, foam concentrate and expanded foam during the test. They were calibrated in ml.

Figure 3.5 - Scale and Measuring Containers

3.1.6 Test Pans

Pan sizes with dimensions 480 x 480 x 200 mm and 690 x 690 x 200 mm were constructed for the pool fire tests. The two test pans were similar to those used for 1B and 2B fire ratings as per UL 8. An ignition pan with dimensions of 400 x 400 x 100 mm was used for the tests. A 100 x 100 x 60 mm pan with an opening at the lower part of the pan was used to determine the drainage characteristics of the foam as shown in Figure 3.6.

Figure 3.6 - Test Pan for drainage test

3.1.7 Stand

A stand was used to hold the discharge nozzle at the height of 0.9 m above the ground during the discharge range test. It was used to investigate the horizontal projection of the foam. It has a moveable clip that is adjustable to the desired height.

Figure 3.7 - Stand

3.1.8 Cone Calorimeter

The cone calorimeter was used to study the foam drainage characteristics at various operating conditions [32].

3.1.9 Thermocouples

Type K thermocouples were connected to an NI 9213 analog input to obtain temperature readings during the test as shown in Figure 3.8. The analog input device sends the data through a National Instrument multiplexer (NI cDAQ-9174) to a data acquisition system. The results were displayed on Labview [33] and temperature readings were recorded at every second interval.

Figure 3.8 - Thermocouple multiplex reader

3.2 Portable Compressed Air Foam System

Compressed air foam consists of three major elements namely air, water and foam concentrate. The quality of the generated foam depends on the proportion of these elements. The foam can be characterized as wet, fluid or dry depending on its expansion ratio. The set up for the compressed air foam generating used in the study is shown in Figure 3.9. The set-up consisted of an air compressor, 3-L container, 8-mm diameter plastic hose and a nozzle. A 2-L premixed foam solution in the designated proportion was prepared and poured into the 3-L container. The 3-L container was then pressurized by air at different pressures to create the compressed air foam. The generated foam passes through an 8-mm diameter plastic hose in which compressed air foam is expected to be developed before it is discharged through the nozzle.

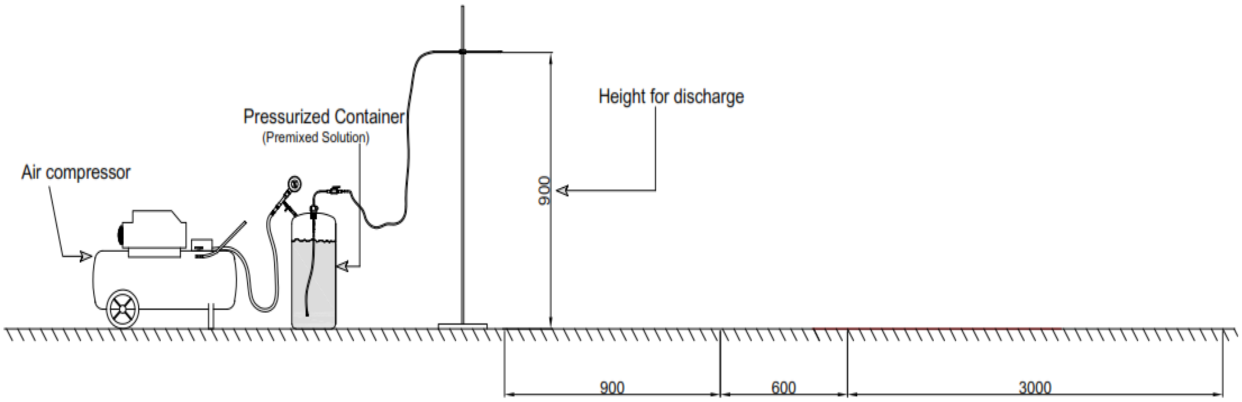

Figure 3.9 - Schematic Diagram of the CAF Generating System Set-up

To achieve a 3 % foam solution, 60 mL of foam concentrate was combined with 1940 mL of water to obtain 2000 mL foam solution. The 2-L foam solution was poured into the 3-L container and pressurized at the designated pressure to create compressed air foam. The generated foam was formed inside the plastic hose and ejected through the nozzle. This procedure was repeated for the 2% solution test and the 4% solution tests.

The expanded foam was collected in a 2000 mL calibrated container and filled to the brim while excess foam was removed by sliding a smooth plank across the top of the container. The weight of the expanded foam was determined on a calibrated scale to a precision of 0.5 g. Subsequent data was collected to ascertain the result. The obtained data was used to calculate the expansion ratio of the aqueous foam. The foam expansion ratio is the ratio of the volume of the expanded foam to the volume of the foam solution at atmospheric conditions. This was used to classify foams into low, medium or high expansion ratio depending of the mixing ratio of water, foam concentrate and air.

3.3 Procedure for Discharge Range Test

The tests were conducted outdoors in a clear weather with little interference of wind. The temperature was consistent, averaging about 18 degrees Celsius at the time of the experiment. The discharge range test was conducted to investigate the horizontal projection of the foam. Figure 3.10 shows a photo captured during a live test with the nozzle placed horizontal at a height of 0.9 m above ground. The yellow lines represent distances of 0.9 m and 1.5 m from the nozzle respectively. Visual record of the discharge range, which is defined as the horizontal distance between the point of highest concentration to the nozzle, was recorded.

Two digital video cameras were positioned around the experiment to obtain visual records, while high resolution digital cameras were used to capture images of the foam and the effect of the wind. The dispersion of the foam was slightly affected by the wind which altered slightly the horizontal discharge of the foam with minor variation.

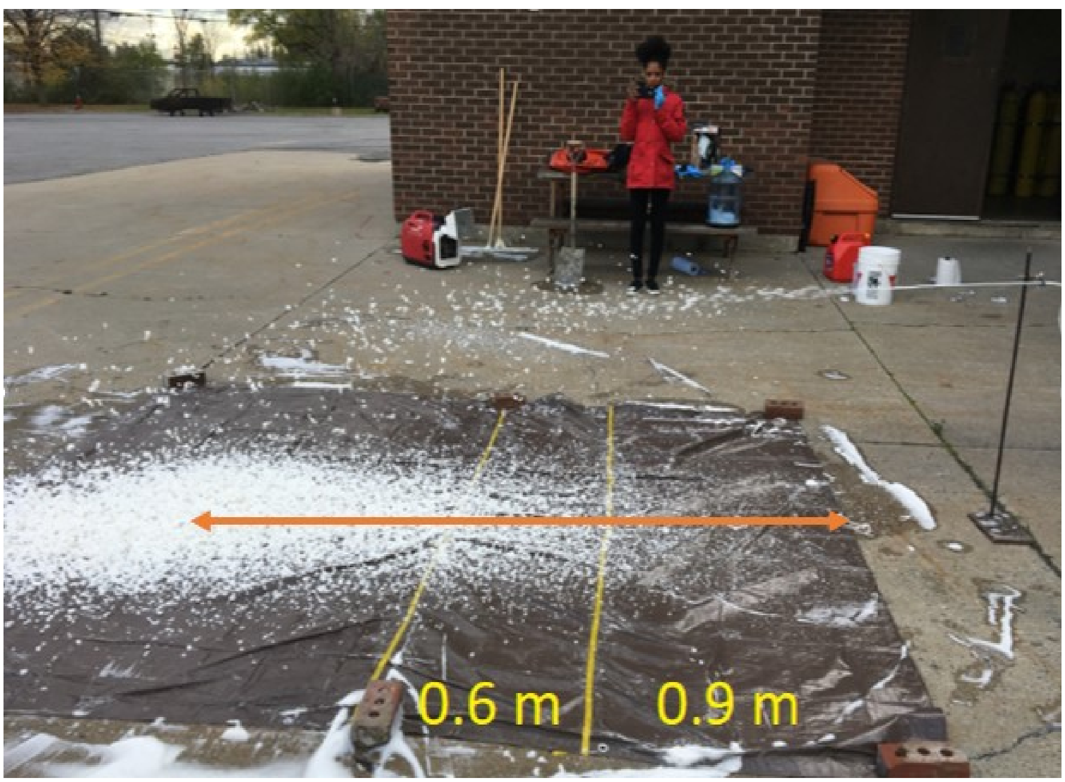

Figure 3.10 - Discharge Range Test

The discharge test was conducted in accordance to CAN/ULC-S508, *"Rating and Fire Testing of Fire Extinguishers"* [10]. It is required that an extinguisher with a capacity under 2.3 kg of agent solution should have an initial discharge of not be less than 1.5 m from the nozzle and a minimum of 90 percent of the discharged foam agent solution shall be effectively discharged beyond a point of 0.9 m from the nozzle. This enable the system to generate foam with sufficient momentum that can penetrate a fire plume and reach the fuel surface as well as provide heat exposure protection to the operator. The discharged foam was evenly dispersed from the nozzle and the foam flow rate was measured at different pressures.

3.4 Procedure for Drainage Test

A small-scale test set up was used to investigate the drainage characteristics of foam as shown in Figure 3.11. The apparatus comprised of a test pan, a drain collection container, thermocouples, a heat flux gauge, radiant heater, measuring scale and a data acquisition system. A cone calorimeter was used to generate a uniform heat flux of thermal radiation on a 60 mm thick aqueous foam layer. The foam sample was placed at a distance of 25 mm below the radiator cone. The drainage characteristics investigated were response of foam to heat, mass loss of foam and foam mass loss rate in relation to the expansion ratio and imposed thermal radiation. The test pan was made of stainless steel with dimensions of 100 mm x 100 mm x 60 mm. The bottom of the pan had an opening of 5 mm in diameter at an edge and was connected to an inclined hollow pipe for drainage collection.

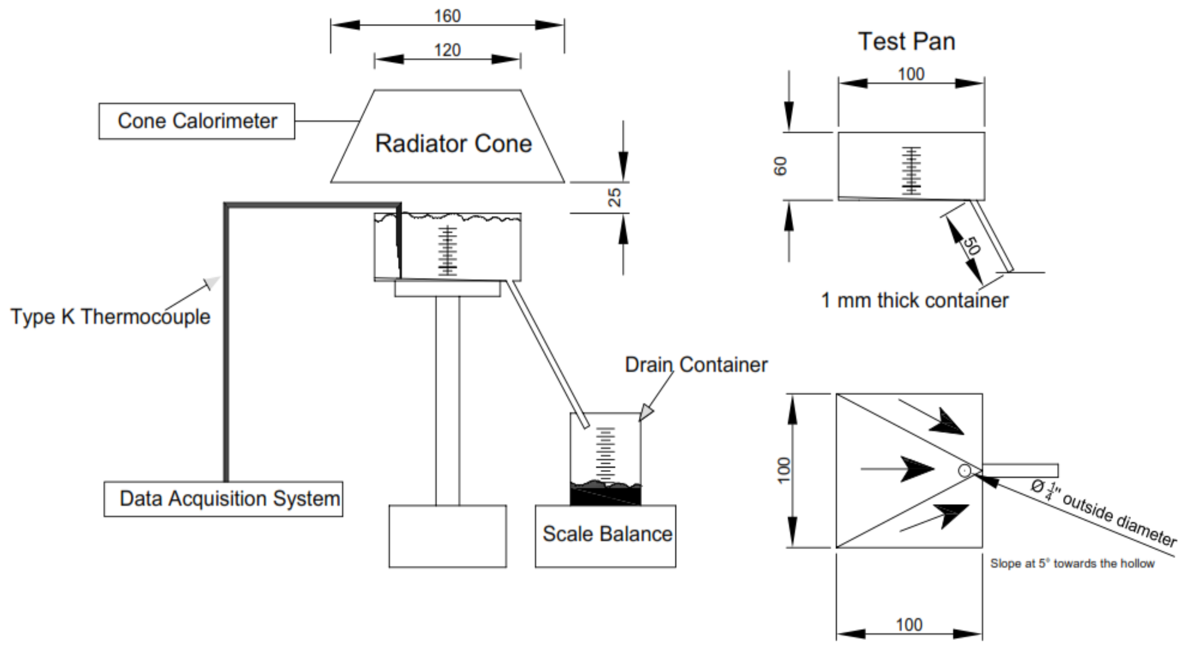

Figure 3.11 - Drainage Test Set Up

Aqueous foam of 60 mm deep layer was generated to the desired expansion ratio by the portable CAF system. The foam was transferred into the test pan and the weight was recorded as shown in Figure 3.12.

Figure 3.12 - Foam Sample

The radiator cone was calibrated and set to the desired heat flux for the test. Type K thermocouples were positioned at four locations inside the sample pan to obtain temperature readings during the test. The first thermocouple (TC1) was positioned at a height of 0 mm, the second thermocouple (TC 2) at 10 mm, the third thermocouple (TC 3) at 20 mm and the fourth thermocouple (TC 4) at 30 mm respectively from the bottom of the test pan. The thermocouples were connected to a National Instrument multiplexer and interfaced with a data acquisition system, Labview, to record data at every second interval. The aqueous foam with different expansion ratios was subjected to constant heat fluxes of 0, 20, 40 and 60 kW/m^2.

3.5 Procedure for Fire Suppression Tests

3.5.1 Pool Fire Tests

The extinguishing performance of the portable system was investigated in a series of tests on pool fires. Pan sizes with dimensions of 480 x 480 x 200 mm and 690 x 690 x 200 mm were used for 0.23 m^2 and 0.47 m^2 pool fires, respectively. See Appendix A for a detailed diagram of the pan with dimensions. The fuel used for the tests was gasoline.

For the experiments, gasoline was used as the ignition source. The fuel was allowed to burn until it reached fully developed phase before commencing fire suppression. The foam was applied in a "bounce off technique" [11] at which the foam was directed at the wall of the pan and allowed to spread over the burning surface to create a thick layer of foam blanket. Fire suppression was achieved after the fire had been extinguished by the foam blanket.

Compressed air foam has a unique property of quick suppression due to its stronger stability and rheology. Fire-fighting foam extinguishes pool fires by simultaneously excluding oxygen from the flammable vapors, eliminates released vapor from fuel surface, separates the flames from the fuel surface and cools the fuel surface.

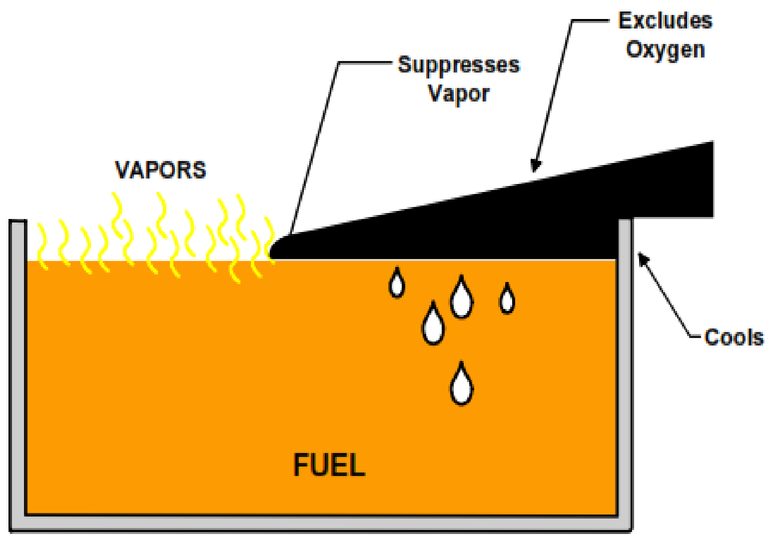

Figure 3.13 - Operating mechanism of fire-fighting foam on pool fire [14]

3.5.2 Wood Crib Fire Test

The extinguishing performance of the portable CAF system on wood crib fires was investigated. Wood cribs were constructed using fir lumber wood type. Details of the wood crib construction are shown in Table 3.1. The wood crib was placed on two angle support and mounted on a metal frame. An ignition pan containing gasoline was placed underneath the wood crib. The fuel was ignited as the wood crib was allowed to lose about 55 % of its mass before activating fire suppression. The suppression technique applied in this case was different from that of the pool fire because wood crib generates a 3-dimensional fire. The fire propagates in all 3 directions. The portable CAF system was used with the gun nozzle for quick suppression. The foam was applied on the wood crib from left to right in both vertical and horizontal directions on all sides during the test. A picture of the wood crib construction is shown in Figure 3.14.

Table 3.1 - Wood Crib Construction

Trade size and length of wood members (mm)	Number of wood members	Arrangement of wood members in crib
38 x 38 x 635	48	8 layers of 6
38 x 38 x 500	72	12 layers of 6

Figure 3.14 - Wood Crib Construction

4 RESULTS AND DISCUSSION

In this chapter, the results of the test series on the discharge characteristics, drainage characteristics and the fire suppression performance of a portable compressed air foam system are presented.

4.1 Discharge Characteristics of a Portable CAF System.

This section describes a series of tests conducted to study the discharge characteristics of a portable CAF system. The experiments investigated the effect of air pressure and hose length on expansion ratio, discharge range of the foam and foam flow rate as a function of pressure.

4.1.1 Effect of Air Pressure and Hose Length on Expansion Ratio

A series of tests was conducted to determine the effect of air pressure and hose length on the expansion ratio of the foam. Foam solutions ranging from 2 % to 4 % with three different hose lengths of 1 m, 2 m and 3 m were subjected to pressure in the range from 2.42 bar to 5.52 bar. The results of the tests are shown in Figures 4.1- 4.3.

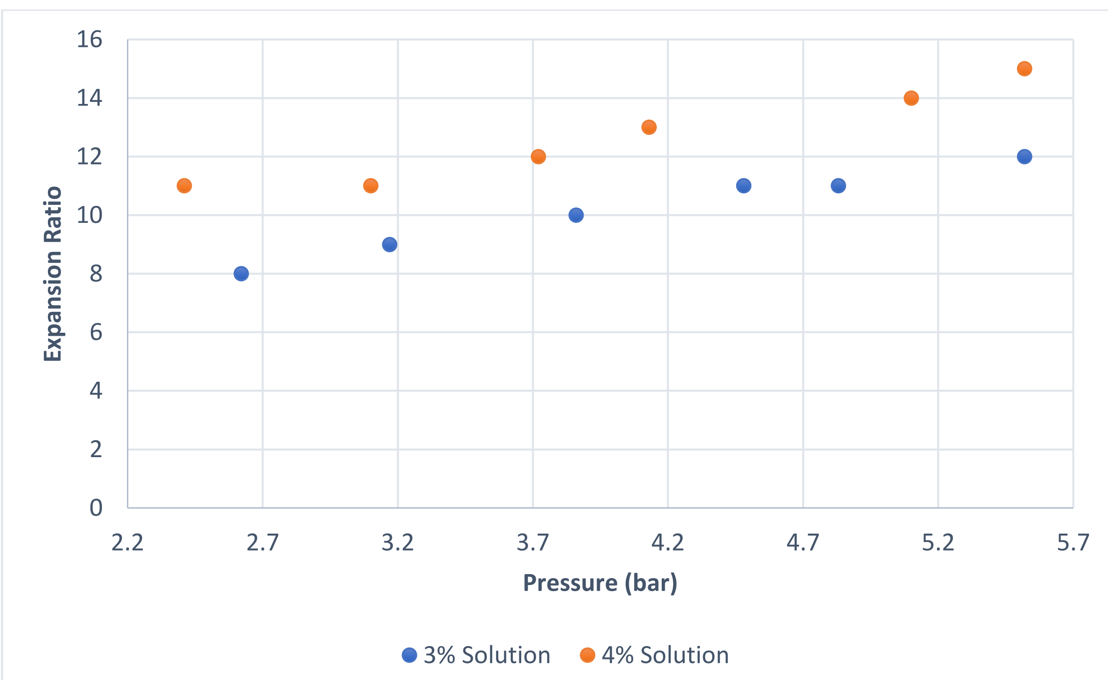

Figure 4.1 - Expansion ratio for 1-m hose

Figure 4.1 shows the effect of pressure on the expansion ratio of 3 % and 4 % foam solution for a 1-m hose. From the graph above, the 4% solution generated foams of higher expansion ratios than the results obtained with the 3% solution for all pressures. The 3 % solution generated foams with expansion ratios in the ranges of 8 and 12 while the 4 % solution generated foams with expansion ratios in the ranges of 11 and 15. Both solutions generated wet foams with low expansion ratios because the foams were partially developed inside the short hose. The foam expansion ratio increased monotonically with increasing pressures for both solutions.

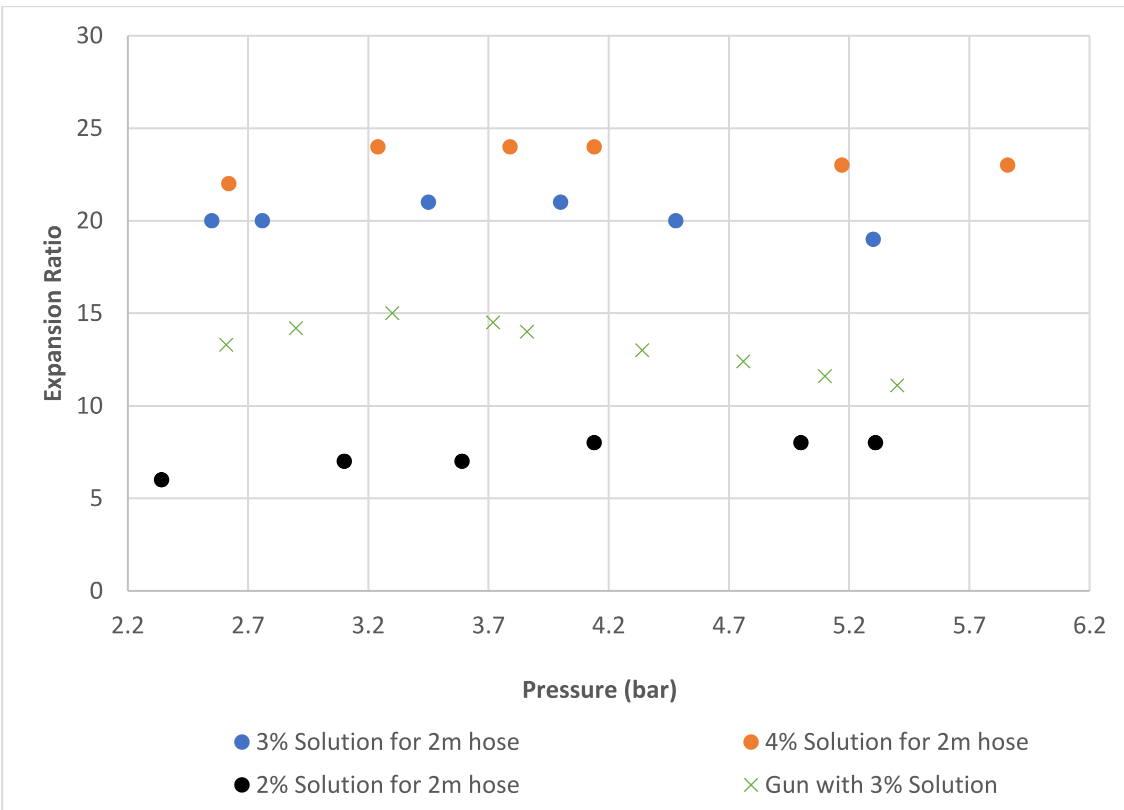

Figure 4.2 - Expansion ratio for 2-m hose

Figure 4.2 shows the effect of pressure on the expansion ratio of 2 %, 3 % and 4 % foam solution for a 2-m hose. Two types of discharge methods, namely tube and tube with gun-nozzle, were used for the test. Similarly with the previous tests, solutions with high foam concentrates generated foams of higher expansion ratios. The 3 % and 4 % foam solutions generated fluid foams with medium expansion ratio in the ranges of 19 and 24 while the 2 % solution generated wet foam with low expansion ratio in the ranges of 6 and 8. The tube with gun-nozzle generated foams with expansion ratio in the ranges of 11 and 16. The 3 % and 4 % solution for both discharge methods generated steady and consistent foams with little variations in expansion ratios over a pressure range as the foams were fully developed inside the hose before being discharged.

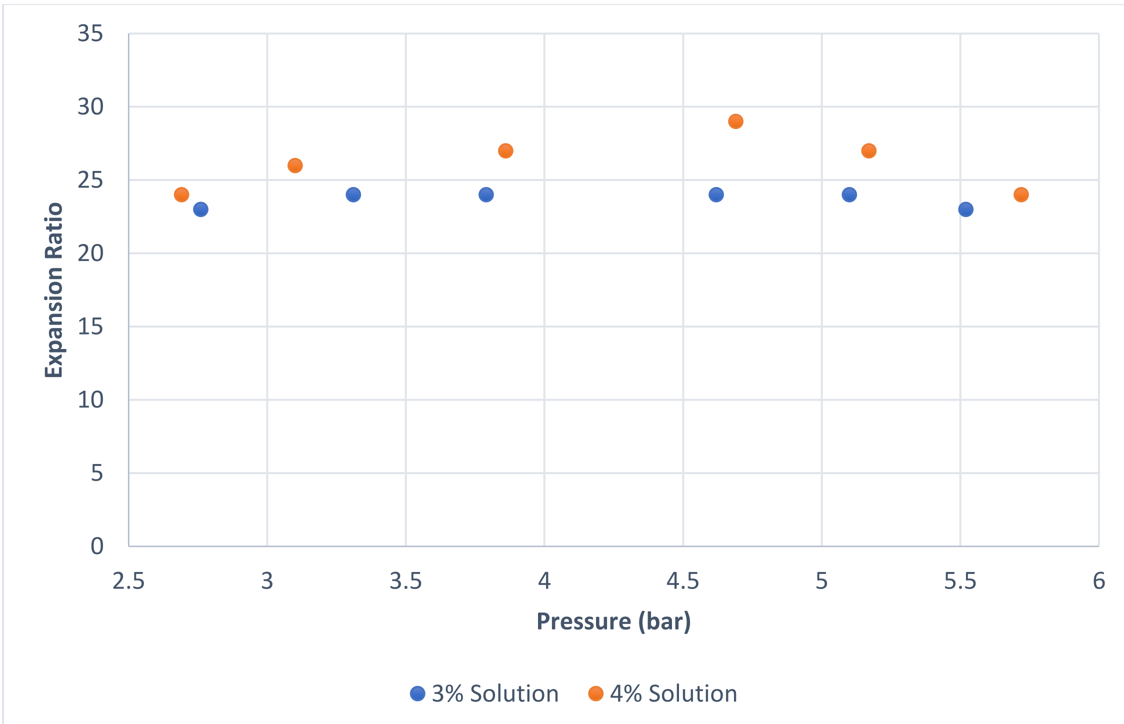

Figure 4.3 - Expansion ratio for 3-m hose

Figure 4.3 shows the effect of pressure on the expansion ratio of 3 % and 4 % foam solution for a 3-m hose. The experimental results exhibited a similar trend with the results of 3% and 4% foam solution for the 2-m hose but with higher expansion ratios, ranging from 23 to 28 for all pressures. The foams were fully developed inside the hose with little effect of pressure on the expansion ratio. The foams are categorized as fluid foams with medium expansion ratios.

Overall, solutions with high foam concentrate generated foams of higher expansion ratio for the same hose length but the foam characteristics, in terms of how wet or dry, depend on the development of the foam in the hose length. From the results, the 2-m hose and 3-m hose could generate uniform and consistent foam over a pressure range of 1.72 bar and 5.52 bar for 3% and 4% foam solutions.

Wet foams of low expansion ratios are effective in extinguishing liquid pool fires while fluid foams of medium expansion ratios are suitable for heat exposure protection of structures due to their slow drainage time and ability to adhere to sloped, vertical, horizontal and slippery surfaces.

4.1.2 Discharge Range Test

The discharge range tests were conducted in an open space with little interference of wind. The horizontal projection of 3 % solution for 1-m, 2-m and 3-m hose lengths were investigated over a range of pressures as shown in Figure 4.4. The discharge range is defined as the distance from the nozzle at which the foam has the highest concentration.

For the 1-m hose, the initial discharge at 2.42 bar was in the range of 1.0 m from the horizontal nozzle and increased progressively to 1.9 m at 3.45 bar. The discharge steadily increased to 2.25 m at 4.48 bar and finally to 2.4 m at 5.52 bar. However, the initial discharge exhibited a longer projection at 2.42 bar for the 2-m hose by starting off at 1.8 m and increased to 2.7 m at 3.45 bar and to 4.5 m at 5.17 bar. A similar pattern was observed for the 3-m hose with the initial discharge of 1.85 m at 2.41 bar, 2.6 m at 3.31 bar and above 4.5 m at 4.83 bar.

For the 1-m hose, the generated foam comprised of high percentage of water content due to partial development of the foam in the hose whereas the foams in the 2-m and 3-m hose projected longer at higher momentum as the foams were fully developed inside the hoses. Overall, the discharge range test for the three hoses met the requirements of the CAN/ULC-S508 standard [10].

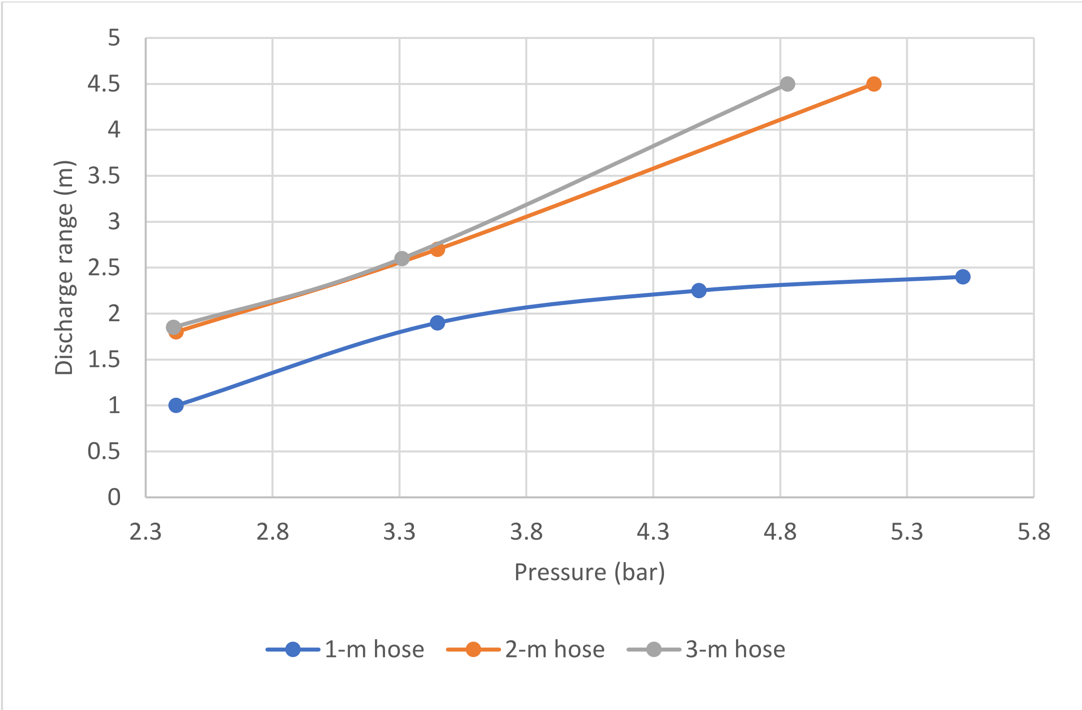

Figure 4.4 - Discharge range test

4.1.3 Flow Rate Test

A 2-L solution in conjunction with a 2-m hose and 3 % foam concentrate was used to investigate the effect of pressure on application time and flow rate as shown in Figure 4.5. The flow rate of the foam increased with increasing pressure from 8 g/s at 1.93 bar to 20 g/s at 5.24 bar. These flow rates correspond to application times of 244 s and 102 s respectively.

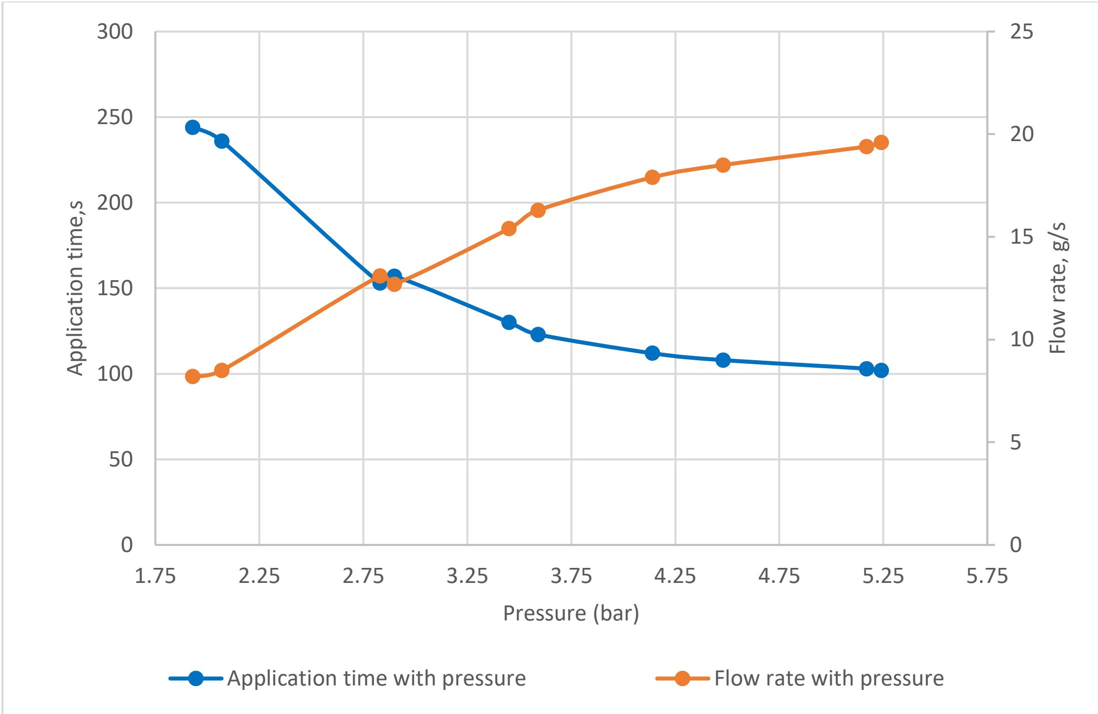

Figure 4.5 - Effect of pressure on application time and flow rate

4.2 Drainage Tests

The drainage characteristics of aqueous foam at different expansion ratios are discussed in this section. The response of foam to heat, foam mass loss of foam and foam mass loss rate were investigated in relation to the expansion ratio and imposed thermal radiation. A constant thermal radiation in the range of 0 - 60 kW/m^2 was imposed on the foam during the tests. Note that the foam expansion ratio is represented by the letter "E".

4.2.1 General behavior of foam when exposed to heat

Fire-fighting foam undergoes several stages of disintegration when exposed to heat. The first stage involves thermal expansion of air bubbles at the upper foam layer as shown in Figure 4.6.

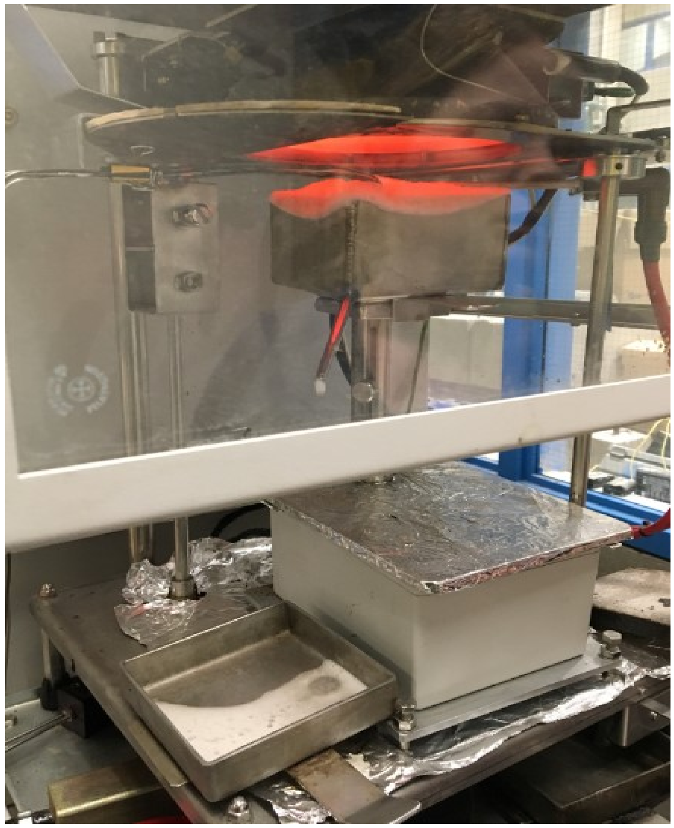

Figure 4.6 - Thermal expansion of foam

As the heat penetrates further, the foam begins to collapse due to evaporation of the foam from the exposed surface and loss of liquid through the discharge outlet. During this period, the drainage rate increases and the underlining foam layers are exposed to intense heat leading to their thermal expansion. The subsequent foam layers begin to collapse as more foam solution drains off and evaporates. As the test progresses, the loss of liquid is reduced and foam mass loss is dominated by evaporation. Magrabi et al. [23] investigated the various stages of foam disintegration in relation to foam height with time. Figure 4.7 shows the effect of radiant heating on foams when subjected to heat fluxes of 10, 20 and 35 kW/m^2. It was observed that the foam decay rate increased with increasing thermal radiation.

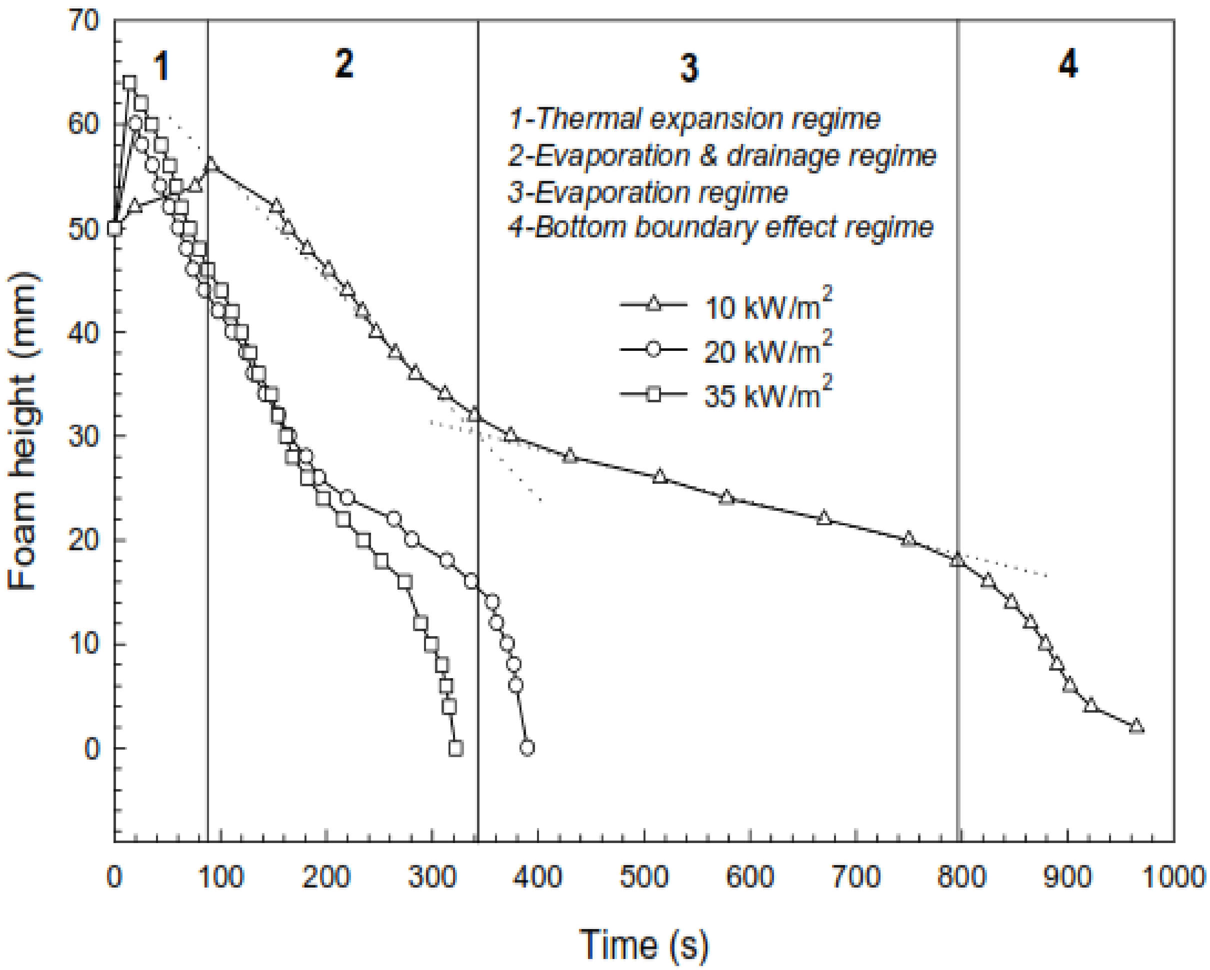

Figure 4.7 - The four regimes of foam disintegration [23]

4.2.2 Response of foam to heat

The response of the foam when subjected to constant radiant heating was studied by placing thermocouples at a height of 0 mm (TC 1), 10 mm (TC 2), 20 mm (TC 3) and 30 mm (TC 4) respectively from the bottom of the test pan. Foams with expansion ratio ranging from 9.7 to 15.8 were subjected to thermal radiation of 20 kW/m^2, 40 kW/m^2 and 60 kW/m^2. The results are presented in this section.

i. Effect of 20 kW/m² heat flux on the foam with an expansion ratio of 10.5

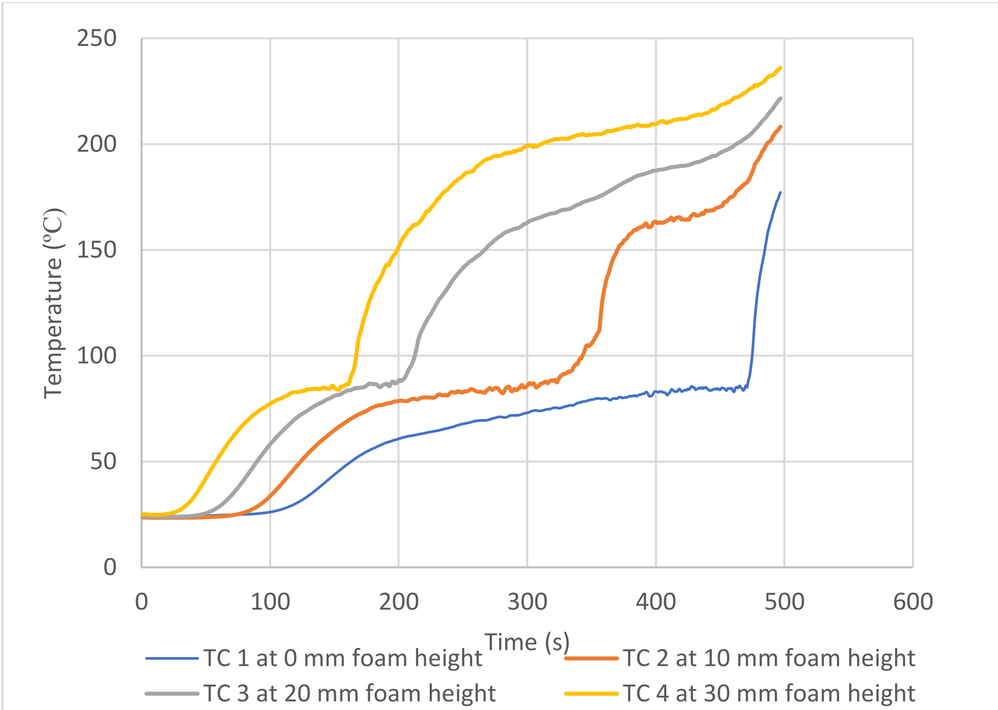

Figure 4.8 - Temperature profile of foam with E = 10.5 at a constant heat flux of 20 kW/m²

Figure 4.8 shows the temperature profiles of the foam with E = 10.5 at a constant heat flux of 20 kW/m². Thermal expansion of the upper 30 mm thick foam layer was observed during the first 150 s of the test before it began to collapse. At 180 s, the temperature of the upper 30 mm foam layer had rapidly increased above 100°C, indicating the foam disintegration to below 60 mm foam thickness. At this stage, the temperatures of the underlining foam had begun to increase. The foam height was reduced to 20 mm at 212 s as shown in Figure 4.9 due to intensive foam evaporation and solution drainage. It took a while before the next 10 mm of foam depleted due to decreasing incident heat flux on the foam. During this period, the mass loss rate of the foam decreased from an average of 0.02 kg/s.m² to 0.005 kg/s.m² as shown in Figure 4.10. At this stage, most of the solution drainage had ceased as the mass loss of the foam was dominated by evaporation. The drainage rate remained steady until the foam layers had completely depleted. The test lasted for 9 min 34 s. The change in foam height with time is shown in Figure 4.9.

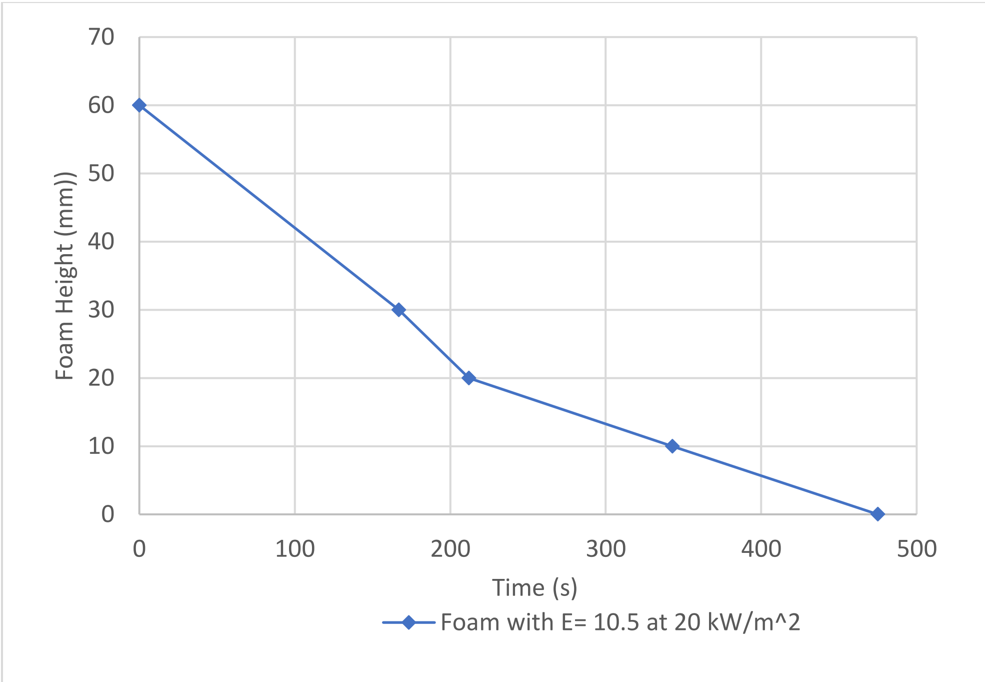

Figure 4.9 - Foam height with time for foam with E = 10.5 at 20 kW/m^2

The mass loss rate of foam was computed from by differentiating the mass loss data recorded during the test, resulting in some oscillation as shown in Figure 4.10.

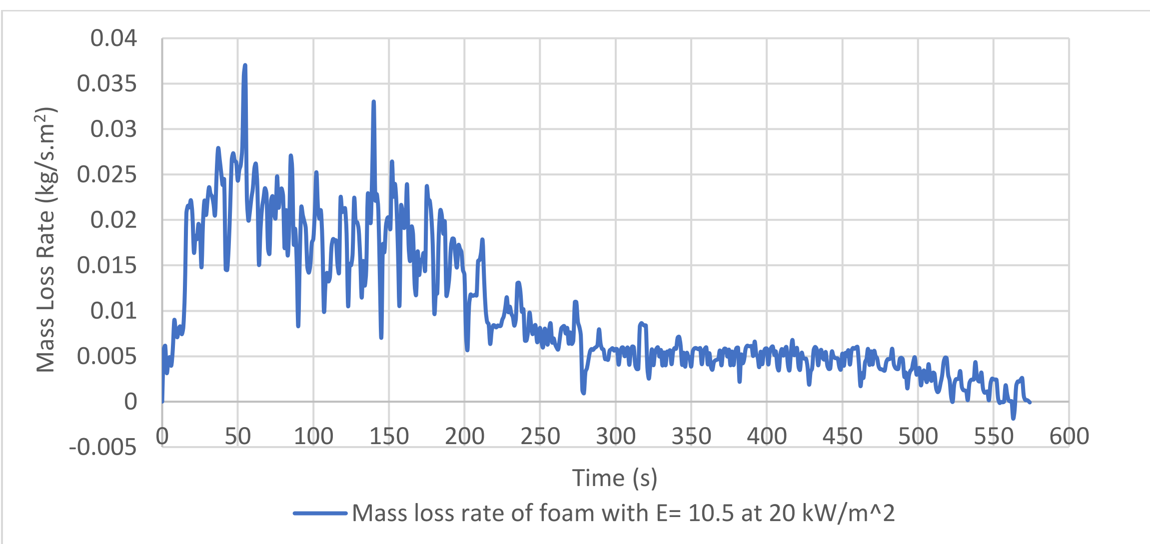

Fig 4.10: Mass loss rate of foam with E = 10.5 at 20 kW/m^2

ii. Effect of 20 kW/m² heat flux on the foam with an expansion ratio of 13.1

Foam with E = 13.1 exhibited a similar temperature profile as the foam with E = 10.5 at the uniform heat flux of 20 kW/m². However, the foam layers depleted at a higher mass loss rate. The effect of the irradiance level on the foam with E = 13.1 is shown in Figure 4.11. During the first 150 s, the upper foam layers were observed to expand and then disintegrate as the incident heat flux penetrated downward. At 155 s, the foam height was reduced to 30 mm as the temperature of TC 4 began to increase exponentially. Likewise, it took another 40 s before the temperature of the next 10 mm of foam began to increase rapidly. The mass loss rate increased to a peak of 0.025 kg/s.m² for the first 100 s before it reduced to 0.005 kg/s.m² during the next 100 s. The remaining 10 mm foam layer continued to disintegrate at a low mass loss rate below 0.005 kg/s.m². The test was stopped at 8 min 18 s after all the foams was completely depleted. The change in foam height and mass loss rate with time are shown in Figure 4.12 and Figure 4.13, respectively.

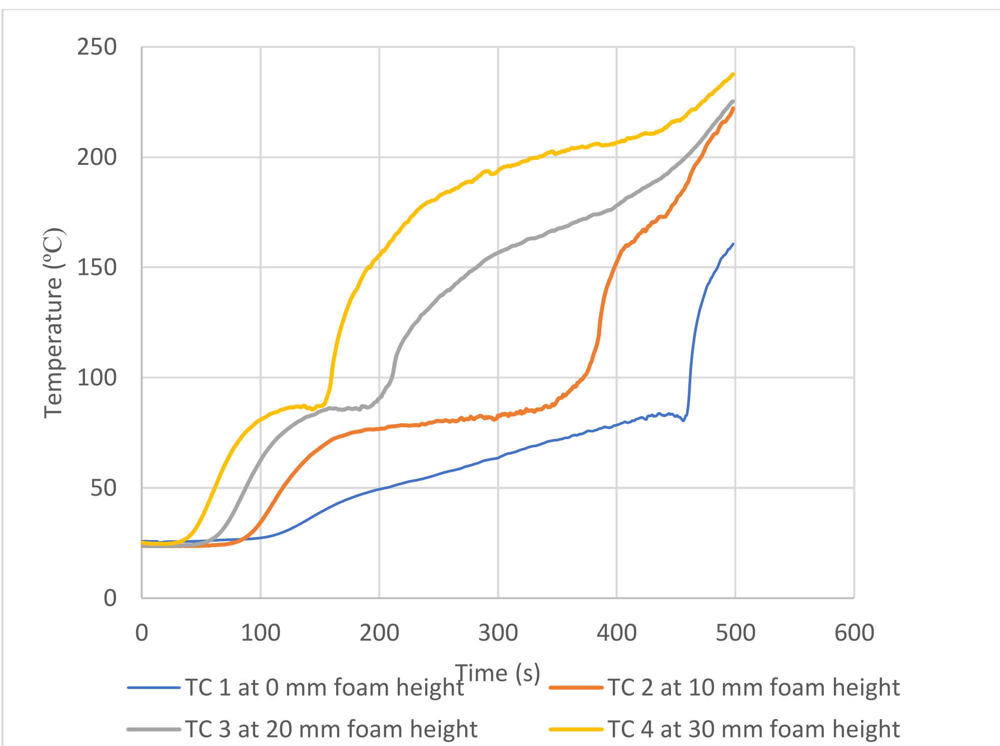

Figure 4.11 - Temperature profile of foam with E = 13.1 at a constant heat flux of 20 kW/m²

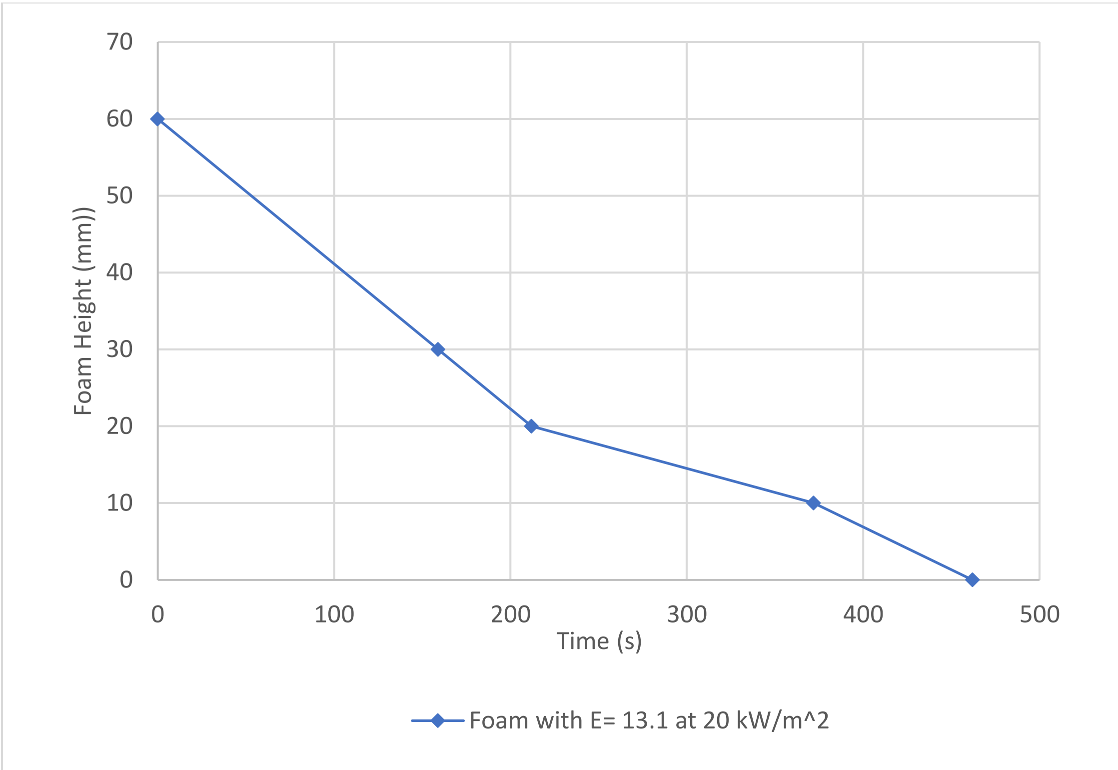

Figure 4.12 - Foam height with time for foam with E = 13.1 at 20 kW/m^2

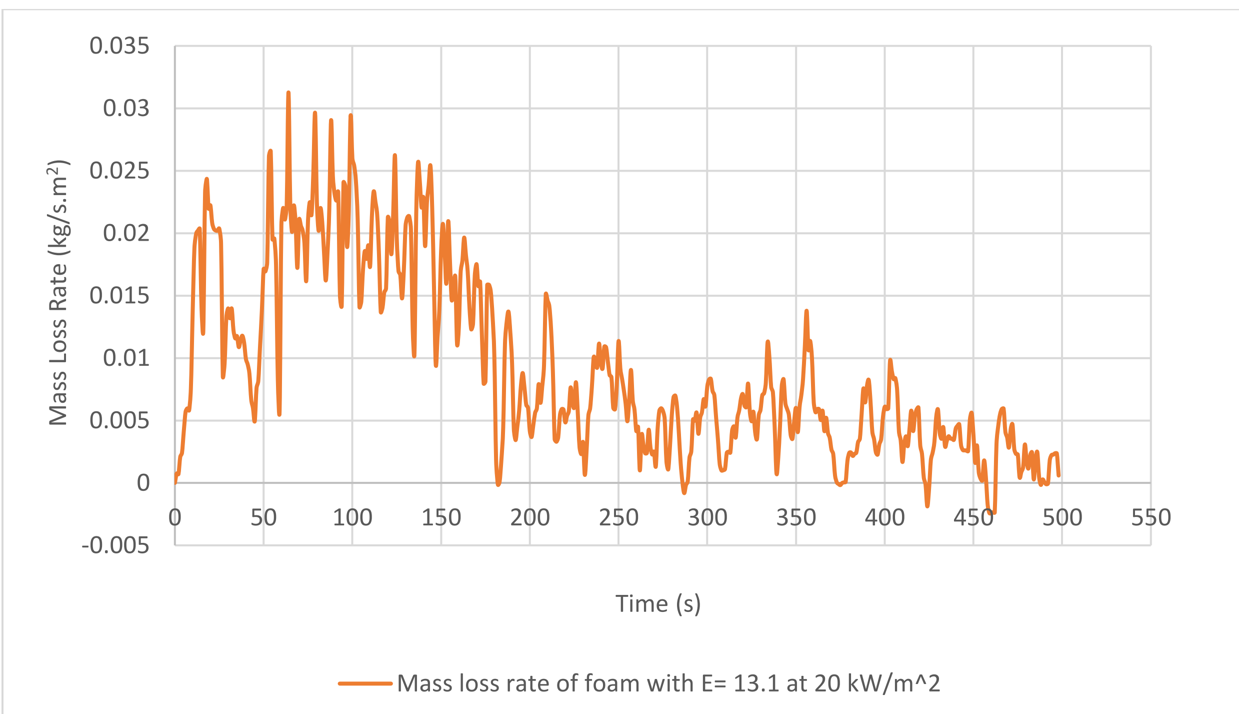

Figure 4.13 - Mass loss rate of foam with E = 13.1 at 20 kW/m^2

iii. Effect of 20 kW/m^2 heat flux on the foam with an expansion ratio of 15.8

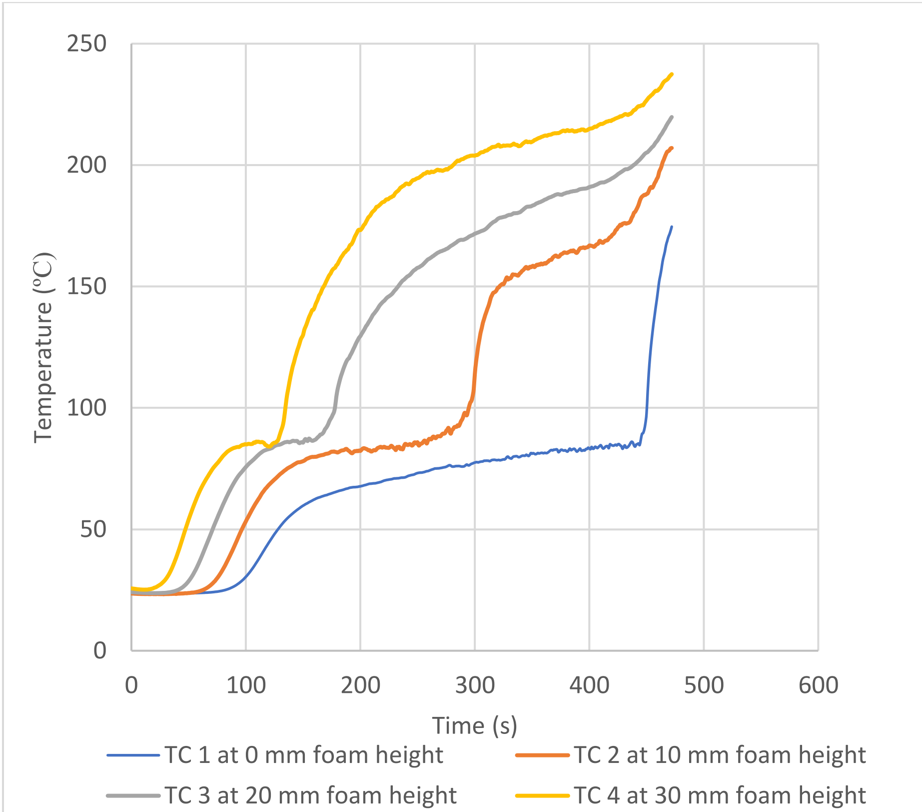

Figure 4.14 - Temperature profile of foam with E = 15.8 at heat flux of 20 kW/m^2

Figure 4.14 shows the temperature profiles of the foam with E = 15.8 at a constant heat flux of 20 kW/m^2. During the first 100 s, the temperatures of the upper 50 mm foam layer increased as the heat penetrated downwards. The foam height was reduced from 60 mm to 30 mm in 122 s. During this period, the upper 30 mm foam layer, as indicated by TC 4, had collapsed thereby exposing the underlining foam layers to intense heat. The mass loss rate rose to a peak of 0.025 kg/s.m^2 in the first 50 s before gradually declining to about 0.0075 kg/s.m^2 at the next 100 s as shown in Figure 4.16. The next 10 mm foam layer depleted after 38 s thereby indicating the period of intense foam evaporation and solution drainage. After 295 s, the foam was reduced to 10 mm and gradually continued to collapse with a mass loss rate below 0.005 kg/s.m^2. The test lasted for 7 min 52 s.

The change in foam height and mass loss rate with time are shown in Figure 4.15 and Figure 4.16, respectively.

Figure 4.15 - Foam height with time for foam with E = 15.8 at heat flux of 20 kW/m^2

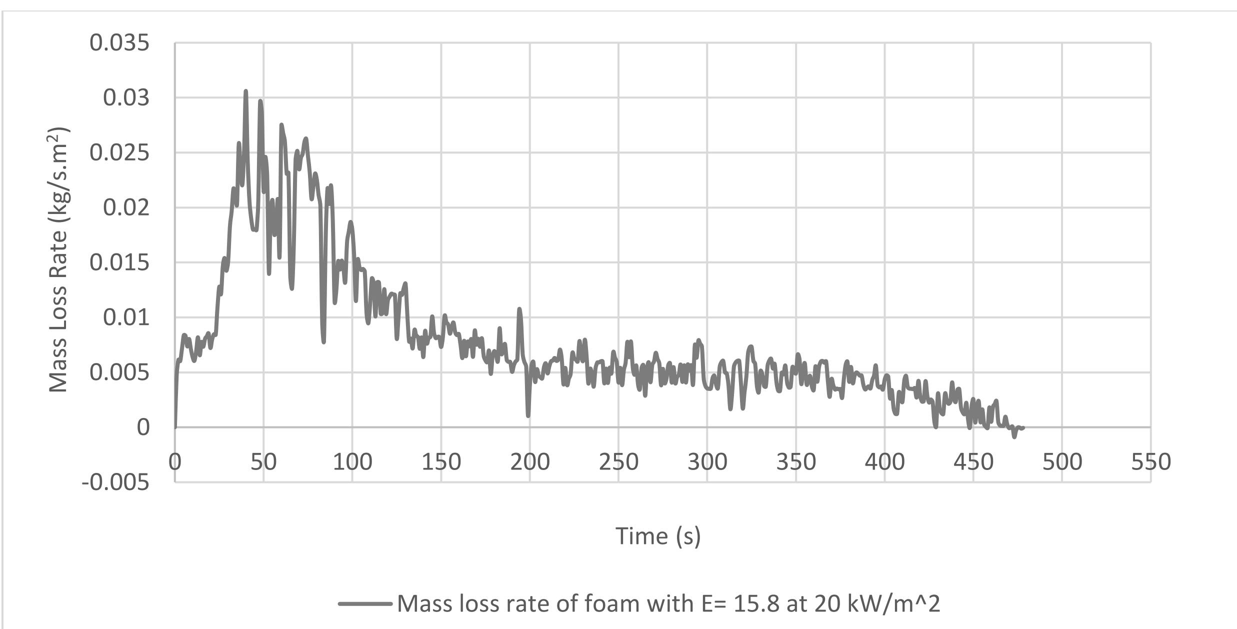

Figure 4.16 - Mass loss rate of foam with E = 15.8 at heat flux of 20 kW/m^2

iv. Effect of 40 kW/m² heat flux on the foam with an expansion ratio of 10.7

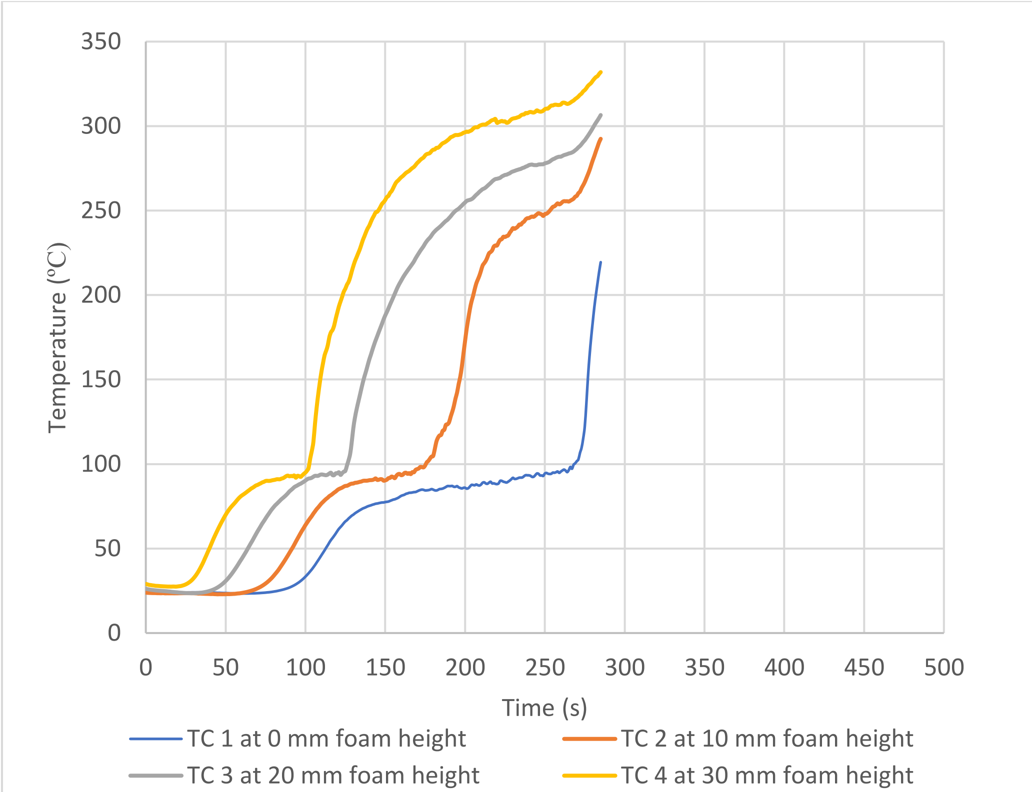

Figure 4.17 - Temperature profile of foam with E = 10.7 at a constant heat flux of 40 kW/m²

Figure 4.17 shows the temperature profiles of the foam with E = 10.7 at a constant heat flux of 40 kW/m². The foam exhibited similar temperature profiles as the previous tests but at a shorter duration. The test took about half the time to completely disintegrate as compared to the test duration for the foam with E = 10.5 when subjected to a heat flux of 20 kW/m². The foam height was decreased to half its size in 102 s and by 10 mm after 24 s. Rapid liquid loss was observed at this stage with an average mass loss rate of 0.03-0.035 kg/s.m². As the test progressed, the mass loss rate began to drop with time due to the decrease of heat flux. At 175 s, the foam height was reduced to 10 mm as the foam disintegrated at an average mass loss rate of 0.01 kg/s.m². The experiment lasted for 4 min 45 s. The graphs of change in foam height and mass loss rate with time are shown in Figure 4.18 and Figure 4.19, respectively.

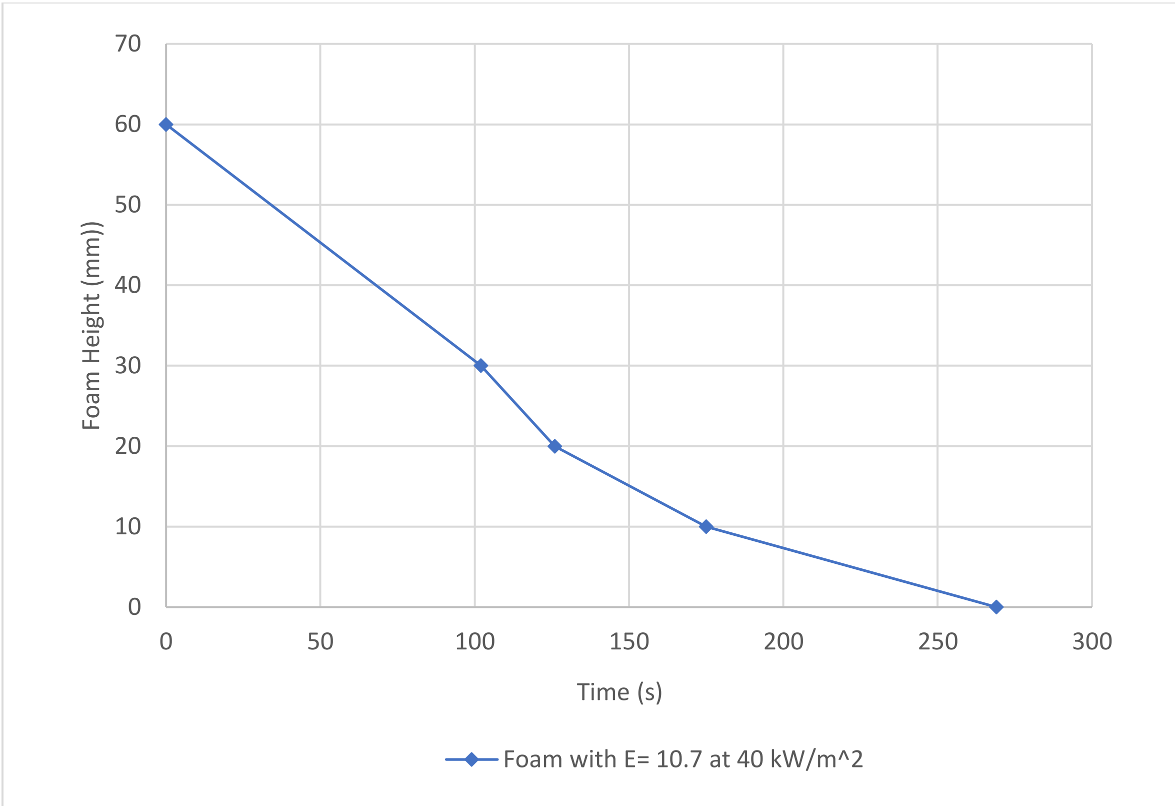

Figure 4.18 - Foam height with time for foam with E = 10.7 at 40 kW/m^2

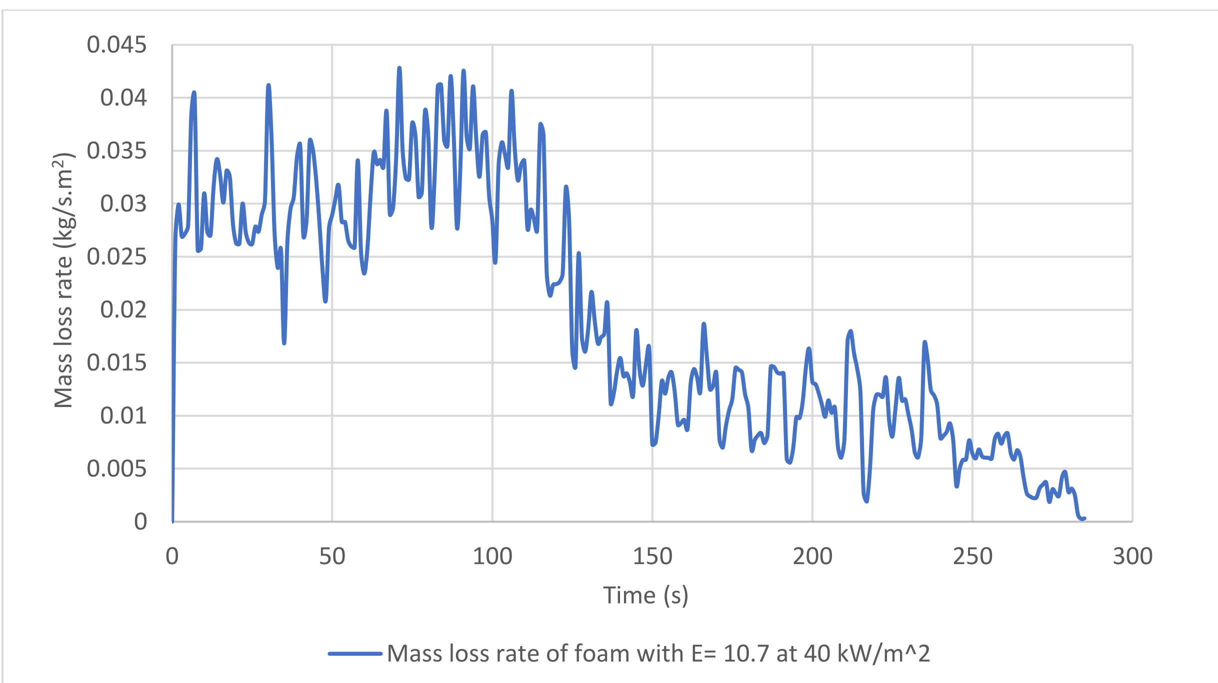

Figure 4.19 - Mass loss rate of foam with E = 10.7 at 40 kW/m^2

v. **Effect of 40 kW/m^2 heat flux on the foam with an expansion ratio of 11.1**

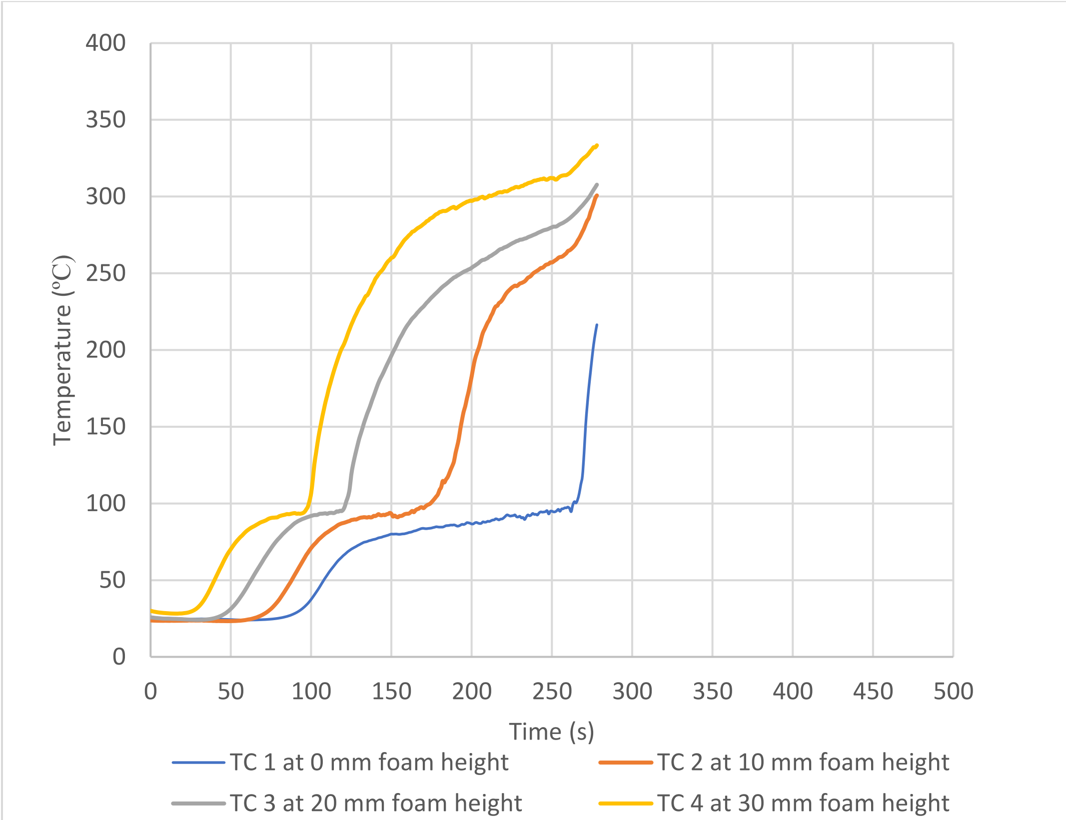

Figure 4.20 - Temperature profile of foam with E = 11.1 at a constant heat flux of 40 kW/m^2

Figure 4.20 shows the temperature profiles of the foam with E = 11.1 at a constant heat flux of 40 kW/m^2. The foam exhibited a similar temperature profile as the foam with E = 10.7 at the same heat flux. The foam destruction rate and mass loss rate with time of the foam with E = 11.1 were slightly higher than the foam with E = 10.7 when exposed to 40 kW/m^2. The experiment lasted for 4 min 38 s. The graphs of change in foam height and mass loss rate with time are shown in Figure 4.21 and Figure 4.22, respectively.

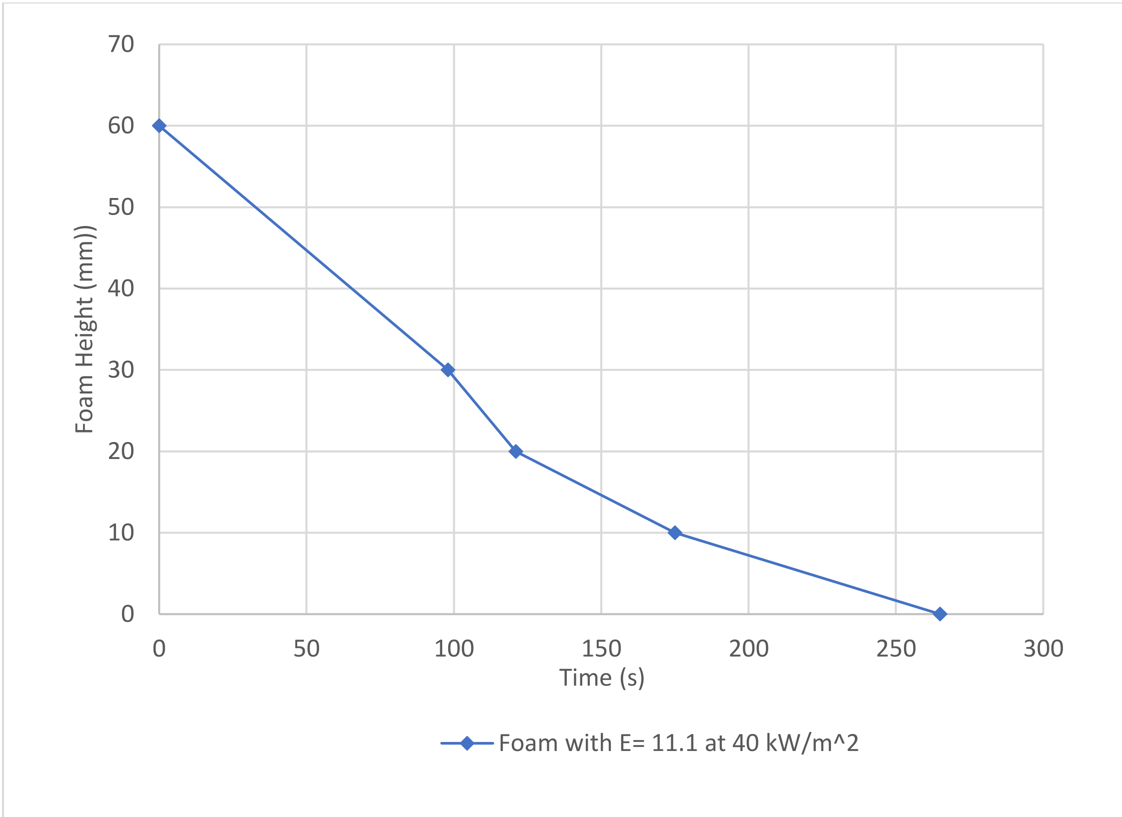

Figure 4.21 - Foam height with time for foam with E = 11.1 at heat flux of 40 kW/m^2

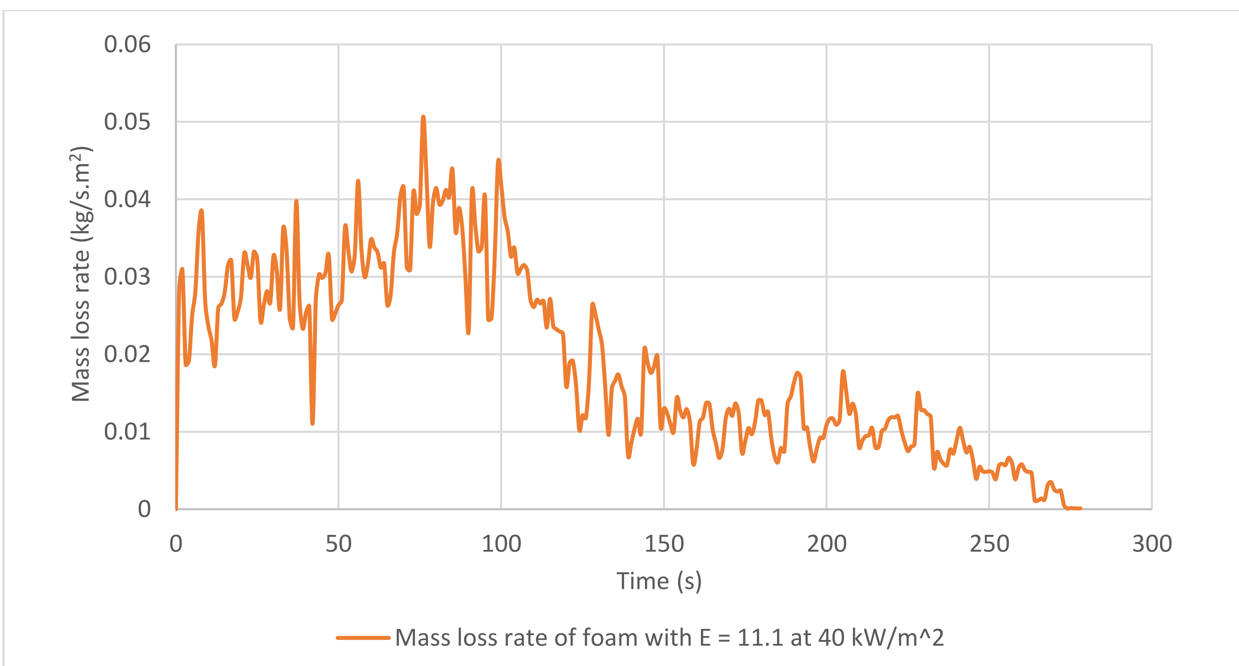

Figure 4.22 - Mass loss rate of foam with E = 11.1 at heat flux of 40 kW/m^2

vi. Effect of 40 kW/m^2 heat flux on the foam with an expansion ratio of 14.6

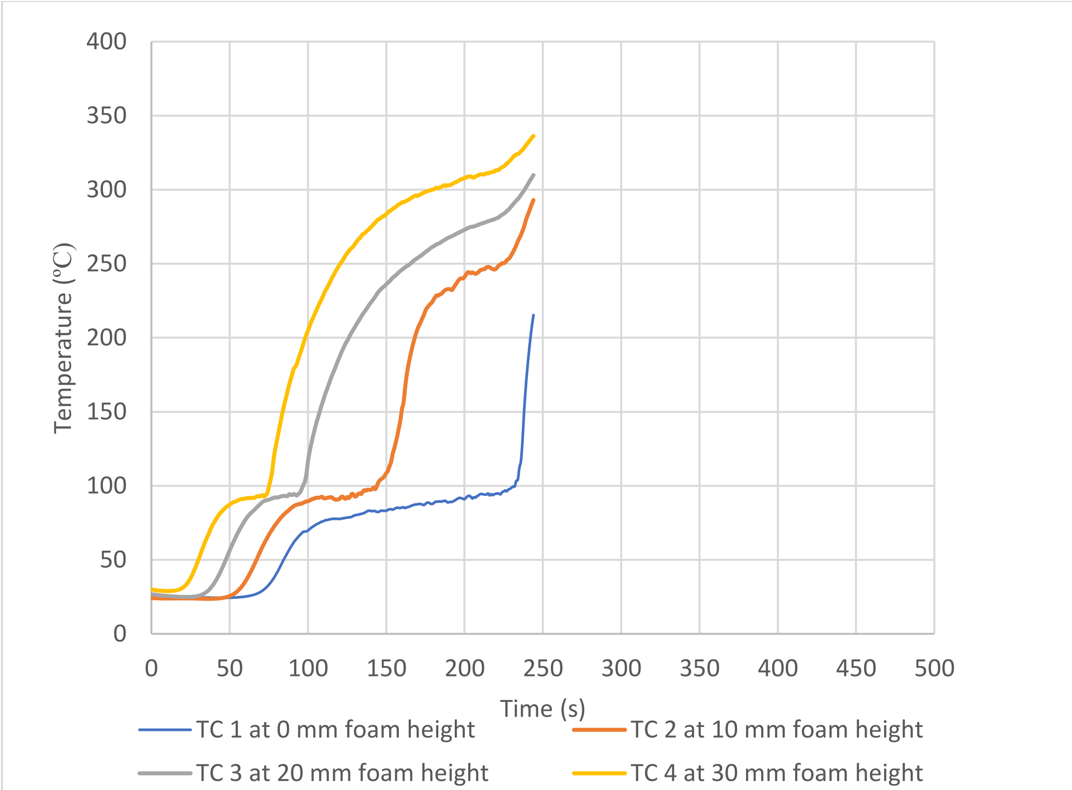

Figure 4.23 - Temperature profile of foam with E = 14.6 at heat flux of 40 kW/m^2

Figure 4.23 shows the temperature profiles of the foam with E = 14.6 at a constant heat flux of 40 kW/m^2. Thermal expansion of the upper 30 mm foam layer was observed after 20 s of heat exposure. Active foam disintegration took place as the temperature of the foam began to increase. The foam height was reduced by 50% at 75 s as the temperature of TC 1 increased exponentially. The mass loss rate during this period increased to 0.04 kg/s.m^2 before experiencing a swift drop. The next 10 mm foam layer collapsed after 22 s at a lower rate. The mass loss rate declined further after 100 s thereby prolonging the foam disintegration of the remaining 20 mm foam layer. At this stage, the loss of liquid had almost ceased while the residual foam evaporated. The experiment lasted for 4 min 4. The graphs of change in foam height and mass loss rate with time are shown in Figure 4.24 and Figure 4.25, respectively.

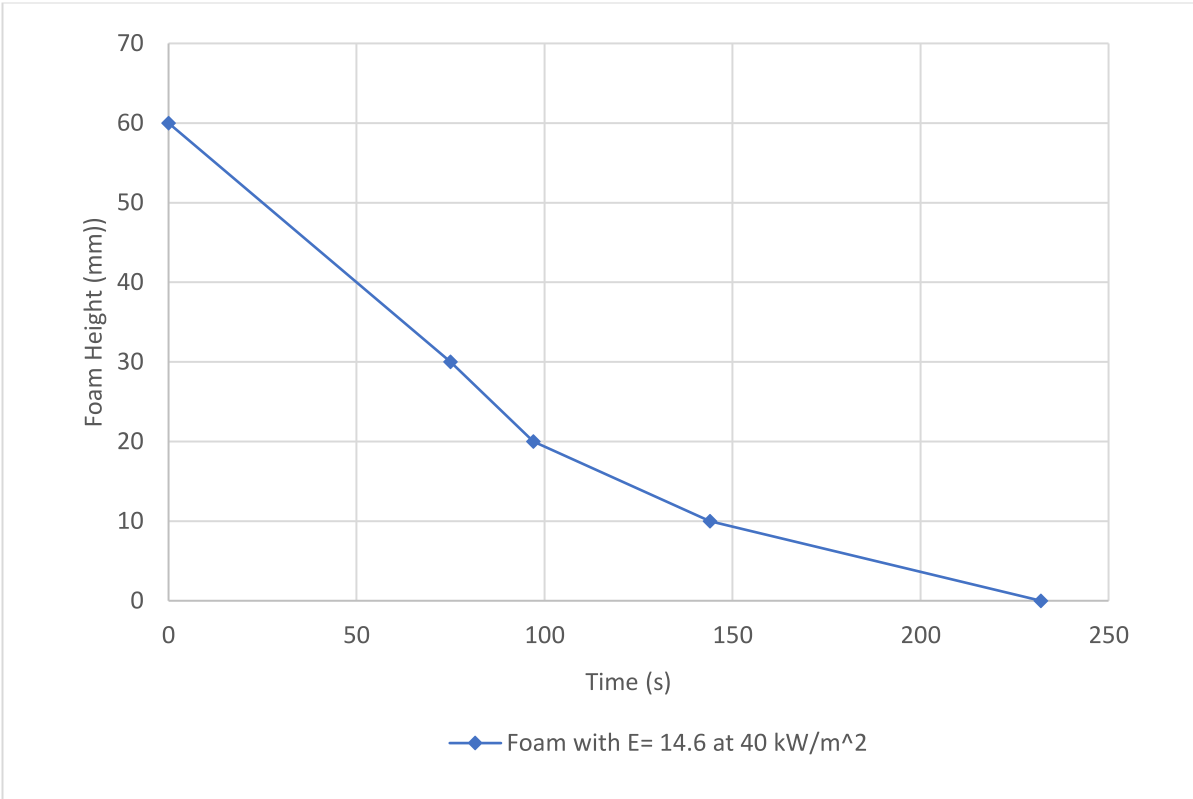

Figure 4.24 - Foam height with time for foam with E = 14.6 at heat flux of 40 kW/m^2

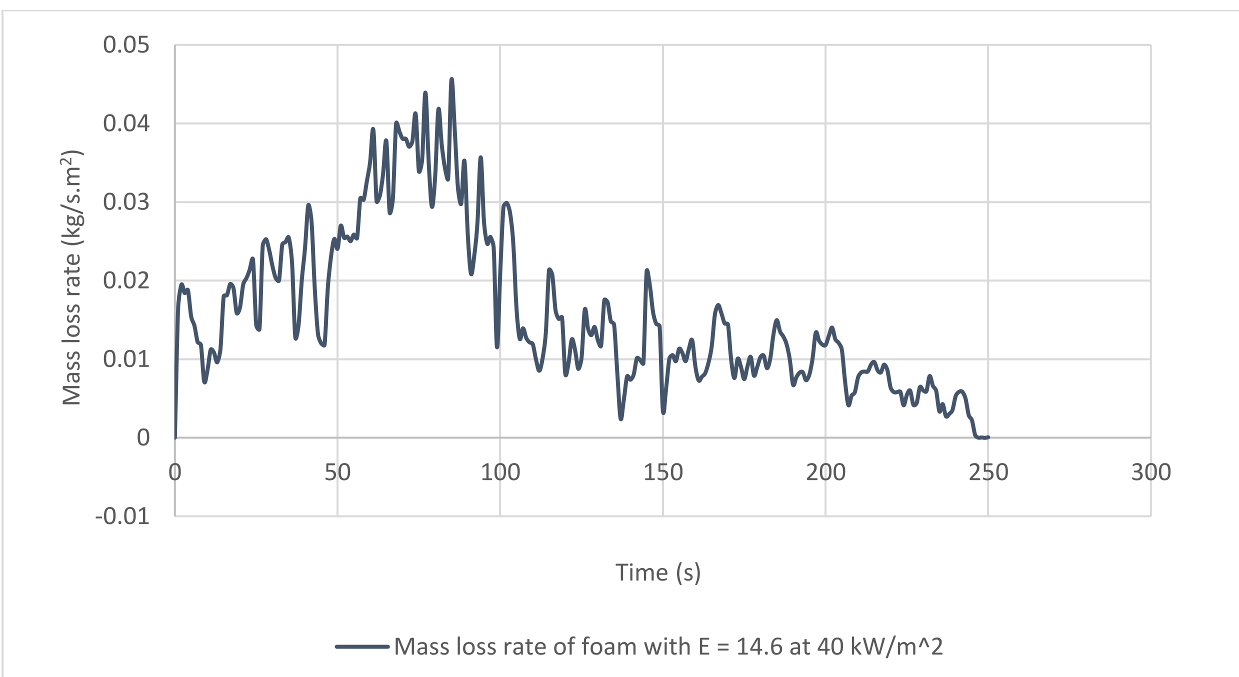

Figure 4.25 - Mass loss rate of foam with E = 14.6 at heat flux of 40 kW/m^2

vii. Effect of 60 kW/m^2 heat flux on the foam with an expansion ratio of 9.7

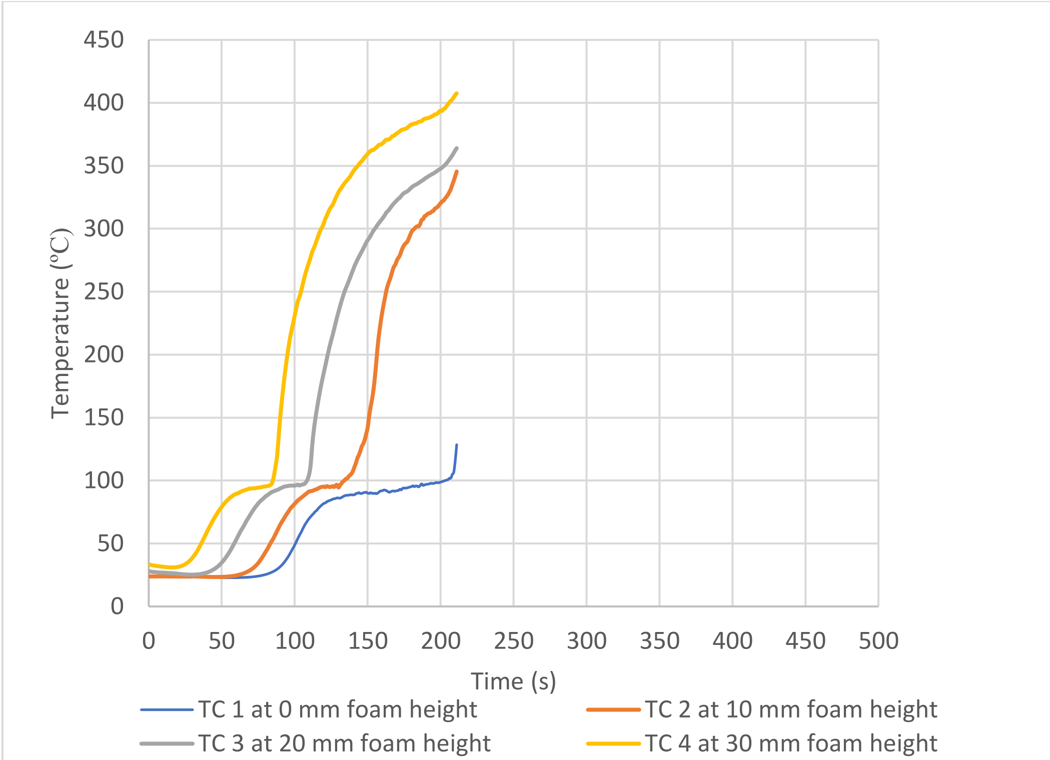

Figure 4.26 - Temperature profile of foam with E = 9.7 at heat flux of 60 kW/m^2

Figure 4.26 shows the temperature profiles of the foam with E = 9.7 at a constant heat flux of 60 kW/m^2. The foam deteriorated faster as compared to foams that were subjected to 20 kW/m^2 and 40 kW/m^2 heat fluxes. However, the pattern of the temperature profile was similar to the previous tests. Rapid thermal expansion and collapse of the upper 30 mm foam layer was observed before reaching 75 s as the heat penetrated through the foam. The temperatures of the foam increased swiftly and exceeded 100 ºC in the first 150 s excluding the last 10 mm foam layer. The foam mass loss by liquid runoff and foam evaporation took place simultaneously at a very fast rate. The mass loss rate ranged between 0.03 and 0.05 kg/s.m^2 in the first 100 s before it began to decrease. At 134 s, the foam height was reduced to 10 mm and the foam disintegrated into vapor at mass loss rate below 0.02 kg/s.m^2. The experiment lasted for 3 min 31 s. The graphs of change in foam height and mass loss rate with time are shown in Figure 4.27 and Figure 4.28, respectively.

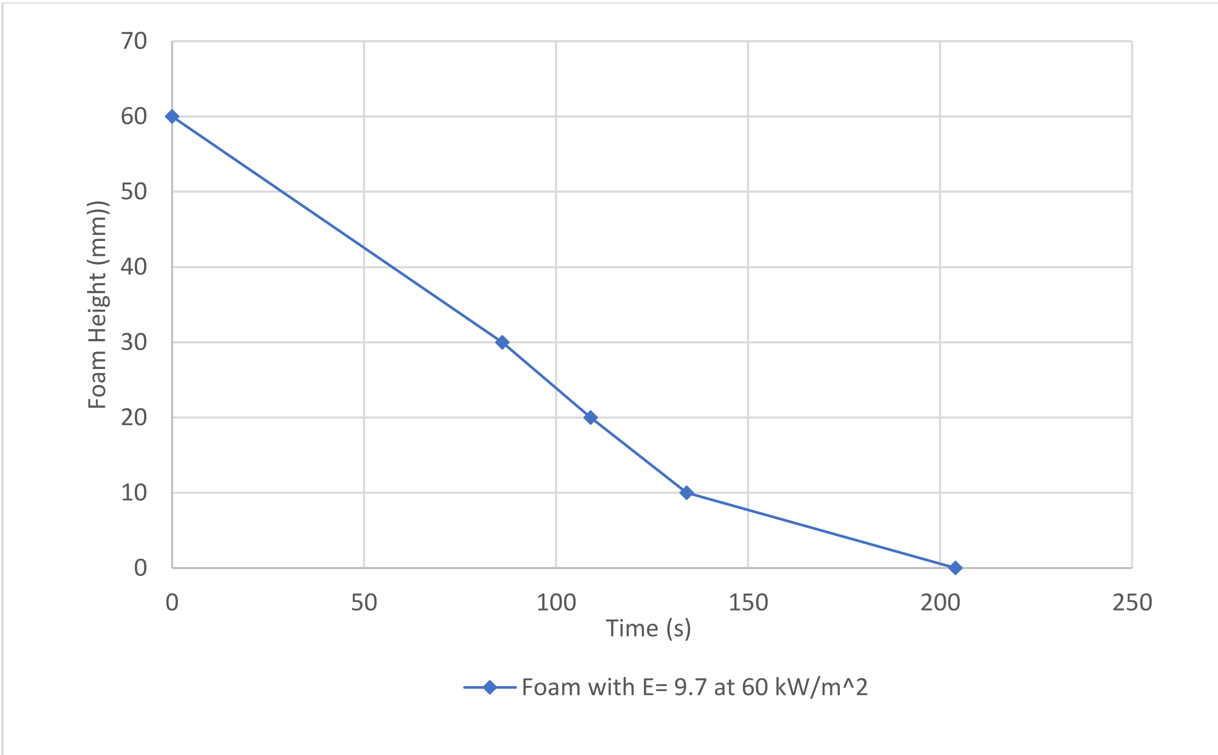

Figure 4.27 - Foam height with time for foam with E = 9.7 at heat flux of 60 kW/m^2

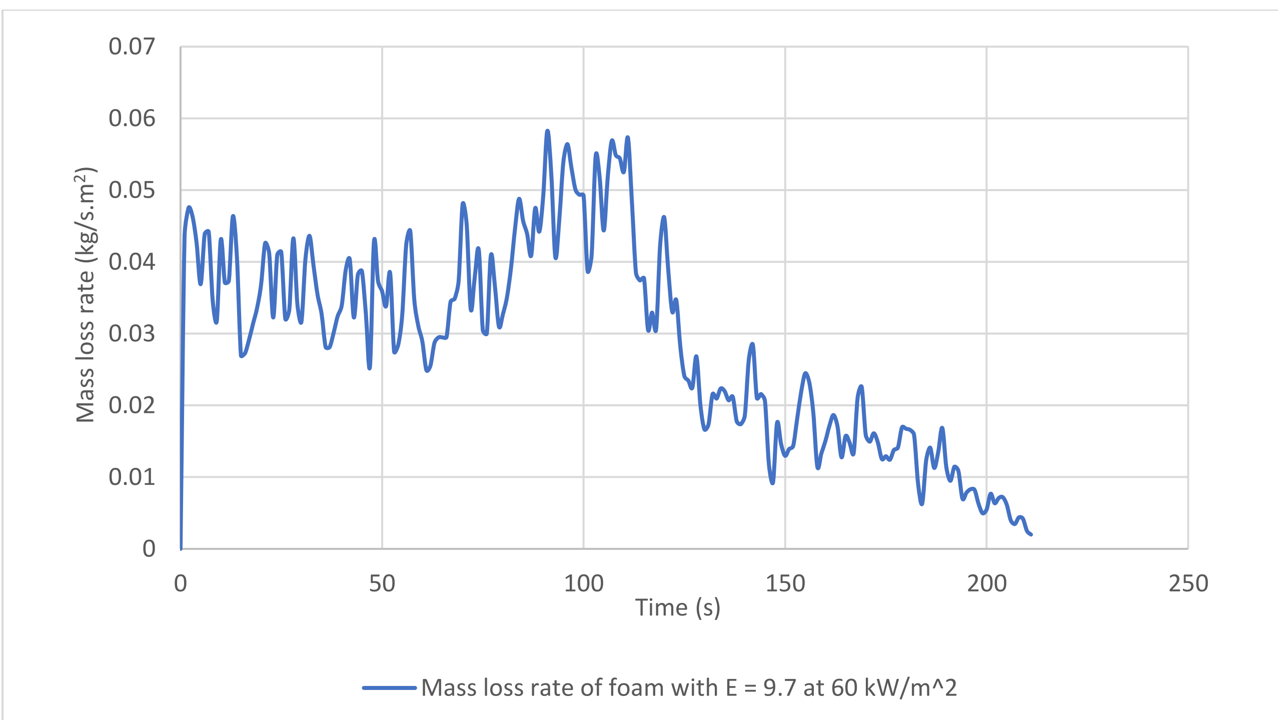

Figure 4.28 - Mass loss rate of foam with E = 9.7 at heat flux of 60 kW/m^2

viii. Effect of 60 kW/m² heat flux on the foam with expansion ratio of 11.6

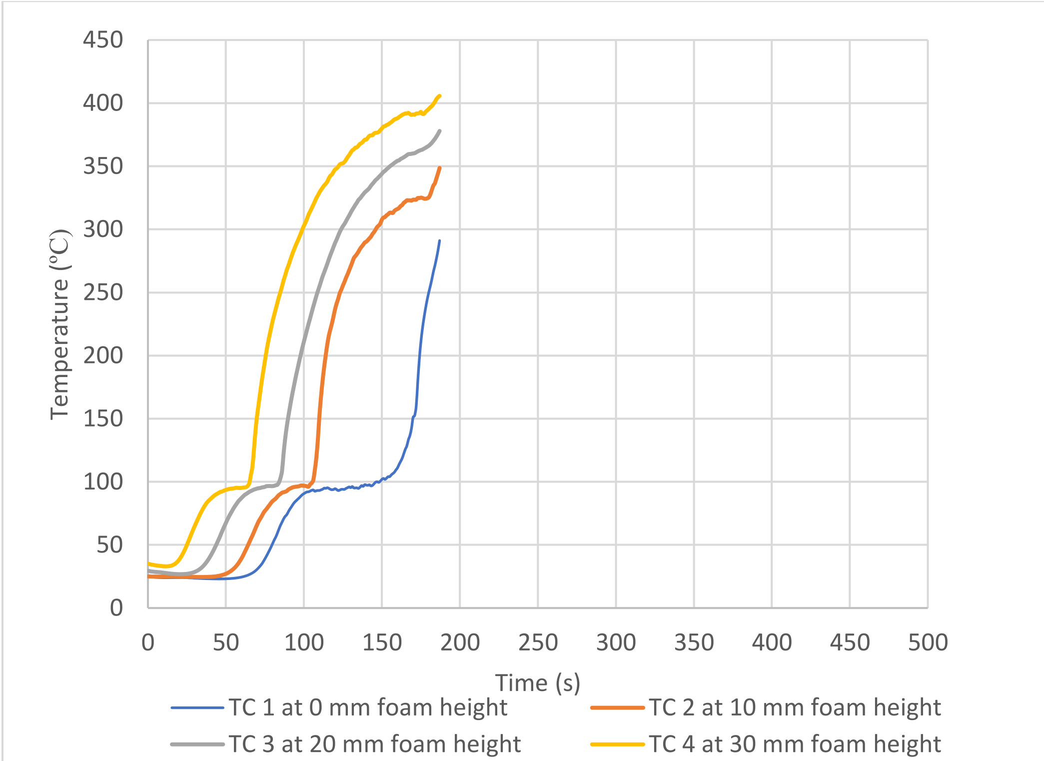

Figure 4.29 - Temperature profile of foam with E = 11.6 at a constant heat flux of 60 kW/m^2

Figure 4.29 shows the temperature profiles of the foam with E = 11.6 at a constant heat flux of 60 kW/m^2. Similarly to the behavior of the foam with E = 9.7 at the heat flux of 60 kW/m^2, the foam reached higher temperatures within a short period. Thermal expansion and foam disintegration occurred simultaneously at an average mass loss rate of 0.03 $kg/s.m^2$ in the first 60 s before increasing to 0.045 $kg/s.m^2$ for 40 s. During this period, the upper 50 mm foam disintegrated due to rapid loss of liquid and foam evaporation. At 100 s, the foam height was below 20 mm as the foam evaporated at a mass loss rate below 0.02 $kg/s.m^2$. The experiment was stopped at 3 min 7 s. The graphs of change in foam height and mass loss rate with time are shown in Figure 4.30 and Figure 4.31, respectively.

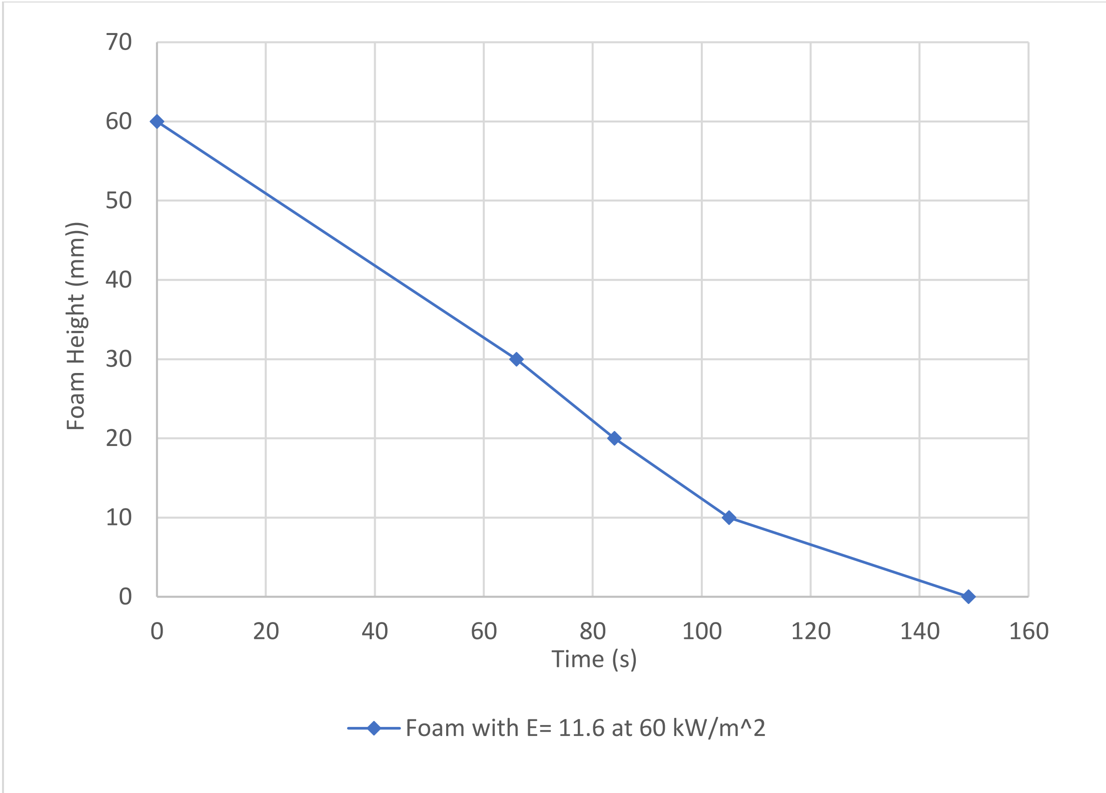

Figure 4.30 - Foam height with time for foam with E = 11.6 at heat flux of 60 kW/m^2

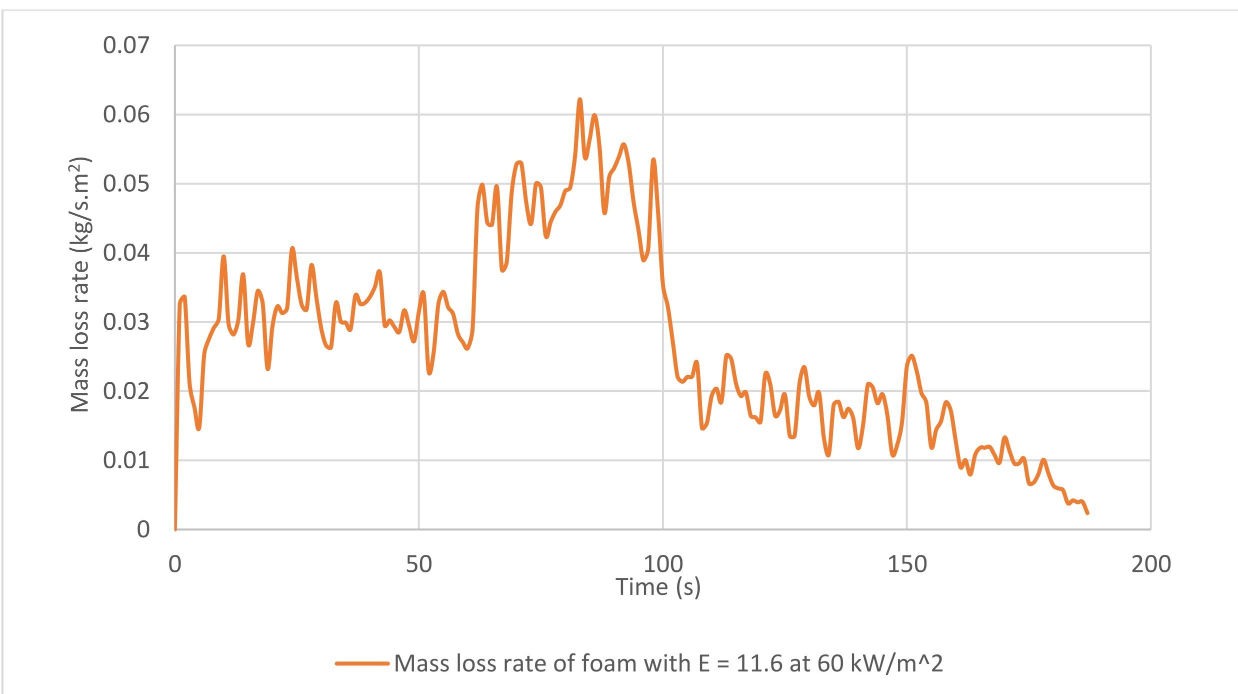

Figure 4.31 - Mass loss rate of foam with E = 11.6 at heat flux of 60 kW/m^2

ix. Effect of 60 kW/m^2 heat flux on the foam with an expansion ratio of 14.1

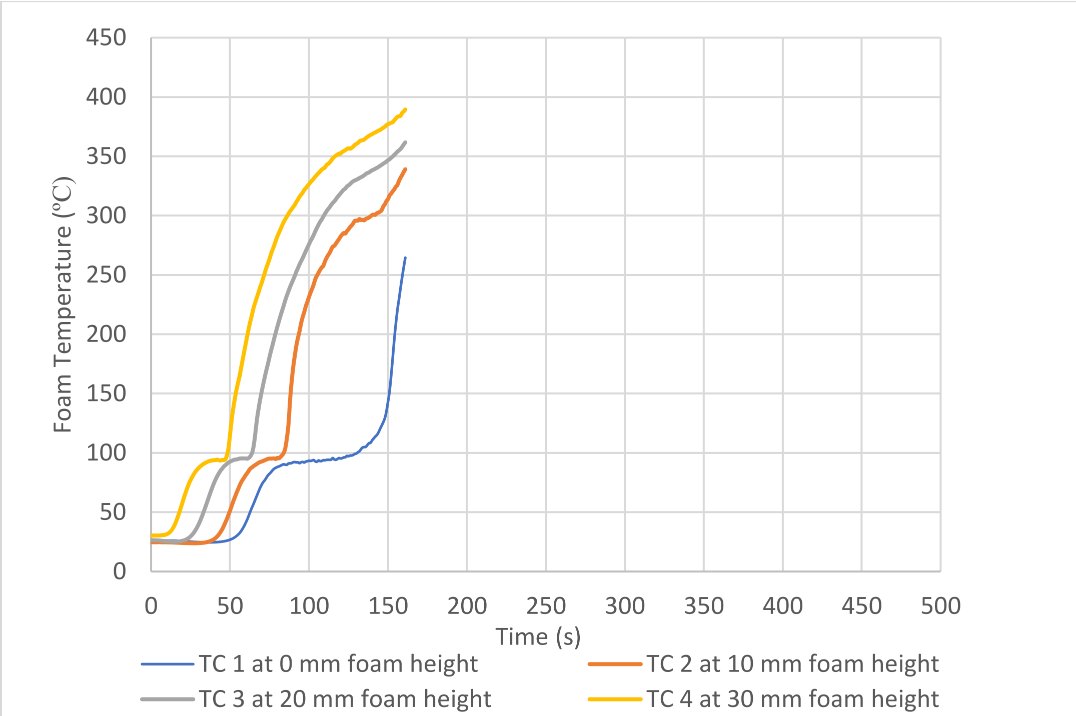

Figure 4.32 - Temperature profile of foam with E = 14.1 at heat flux of 60 kW/m^2

Figure 4.32 shows the temperature profiles of the foam with E = 14.1 at a constant heat flux of 60 kW/m^2. The foam mass loss occurred at a rapid rate as the collapsed foam evaporate and drain off simultaneously. The foam height drastically reduced to below 10 mm as the foam recorded higher temperatures within the first 100 s. The mass loss rate ranged between 0.02 kg/s.m^2 to 0.06 kg/s.m^2 during this period. The remaining foam evaporated at a mass loss rate of 0.02 kg/s.m^2 and below. The experiment lasted for 4 min 4 s. The graphs of change in foam height and mass loss rate with time are shown in Figure 4.33 and Figure 4.34, respectively.

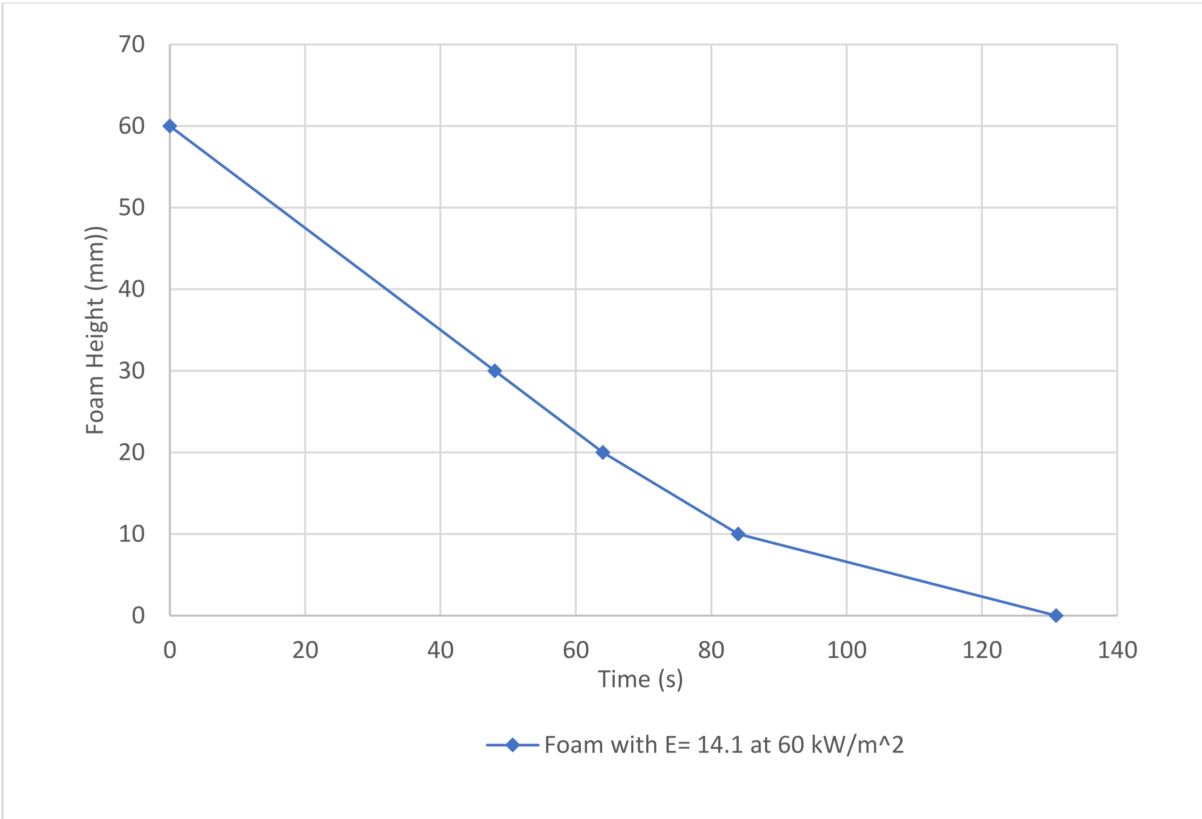

Figure 4.33 - Foam height with time for foam with E = 14.1 at heat flux of 60 kW/m^2

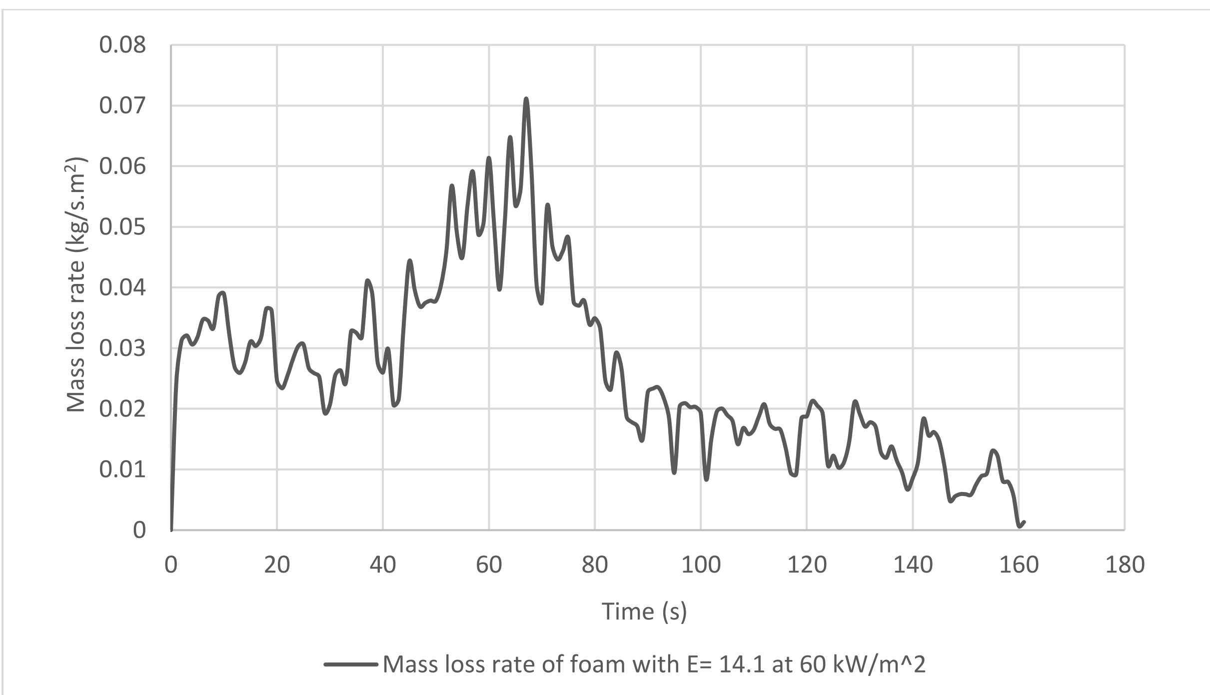

Figure 4.34 - Mass loss rate of foam with E = 14.1 at heat flux of 60 kW/m^2

4.2.3 Comparison of foam mass losses

This section discusses the disintegration of foams at ambient temperature and at the imposed heat fluxes.

4.2.4 Foam mass loss at ambient temperature

Free drainage test of foams were conducted to investigate the mass loss of foams at ambient temperature. Since no heat was imposed during the test, mass loss of foam was mainly by drainage of the foam solution from the foam bed. The drained solution passed through a discharge outlet at the bottom of the test pan under the influence of gravity. Three tests were conducted using foams with E = 8, 9 and 11. The aqueous foam was generated by the portable compressed air foam system. The foam mass loss graphs of the three foams are shown in Figure 4.35.

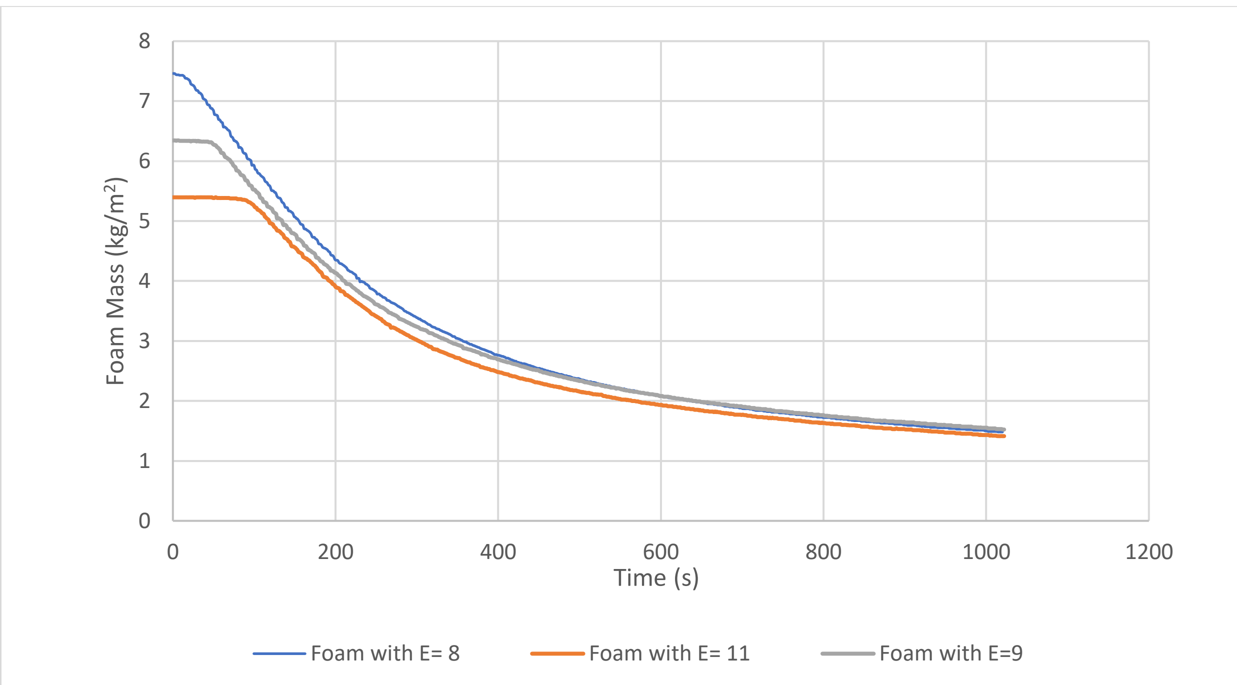

Figure 4.35 - Free drainage of foams with E = 8, 9 and 11 at ambient temperature

Figure 4.35 shows the free drainage of foams with E = 8, 9 and 11 at ambient temperature. The solution drainage of the foam with E = 8 started off almost immediately at a fast rate thereby losing approximately half of its mass in the first 256 s. The drainage rate gradually decreased with time due to the reduction of the liquid flow from the foam bed. At 1020 s, the loss of liquid had ceased, thereby leaving behind dry foams. The weight of the residual dry foam was 15.3 g after 1020 s of free drainage.

The foams with E = 9 and 11 retained their initial masses for awhile before the foams began to disintegrate. Foam with E = 9 retained its initial mass of 64 g for the first 50 s before noticeable changes was observed. The foam exhibited a similar drainage pattern to the foam with E = 8 by flowing at a higher rate after 50 s and then began to decrease with time. The foam reduced to half its mass in 300 s. The percentage of dry foam became higher than that of the drained solution over time. The test was stopped at 1020 s after losing 48.3 g of its mass.

Similarly, the foam with E = 11 retained its mass for the first 90 s before the foam began to collapse. The drainage pattern for the foam was like the foam with E = 9 as the foam lost 50% of its mass after 350 s of free drainage. The test was stopped at 1020 s with no sign of solution drainage. The foam heights for the three tests reduced by an average of 10-12 mm after each tests. The summary of the test results is shown in Table 4.1. Overall, the three tests exhibited similar drainage pattern but at different drainage rates. As the foam expansion ratio increased, the time required for the foam to lose half its mass and the percentage of dry foam increased.

Table 4.1 - Foam mass loss at ambient temperature

Test No	Expansion ratio	Weight of foam sample (g)	Test duration (min:s)	Weight of drained foam (g)	Weight of dry foam in the test pan (g)	Percentage of dry foam (%)	Time to half mass (s)
1	8	75	17:00	59.7	15.3	20.4	256
2	9	64	17:00	48.3	15.7	24.53	300
3	11	54	17:00	39.2	14.8	27.41	356

4.2.5 Foam mass loss by imposed thermal radiation

The drainage characteristics of the foam when exposed to thermal radiation were different from foams without imposed heat. Losses of foam mass are characterized by evaporation of the foam and drainage of liquid from the foam bed. The effects of imposed heat flux on the time for foams to reduce to half their initial masses were investigated.

a) Mass loss of foams at 20 kW/m²

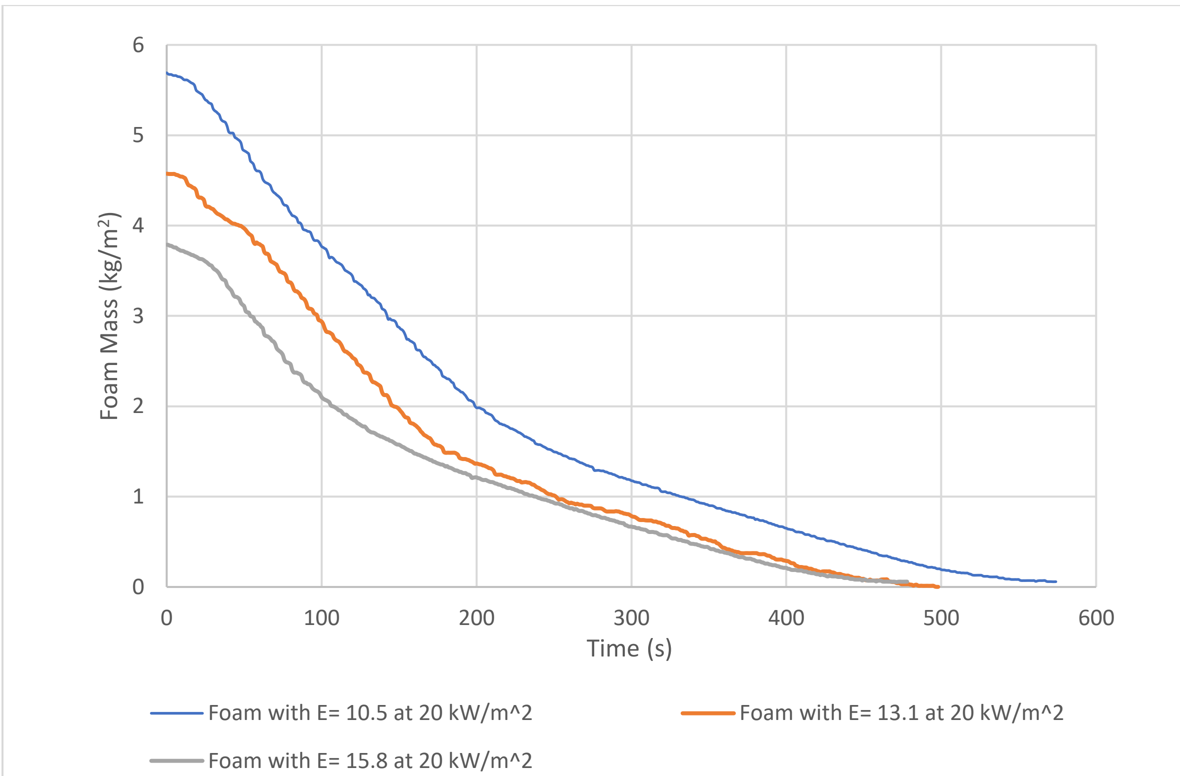

Figure 4.36 - Foam mass loss at heat flux of 20 kW/m²

Figure 4.36 depicts the disintegration of foams with E = 10.5, E = 13.1 and E = 15.8 when subjected to constant heat flux of 20 kW/m^2. The foam with E = 10.5 reduced from 57.2 g to 28.6 g in the first 167 s. After this period, the drainage rate began to reduce with decreasing incident heat flux on the foam as the test progressed. The test lasted for 574 s. Similarly, the foam with E = 13.1 decreased from 45.8 g to 22.9 g in 132 s and the foam with E = 15.8 decreased from 38 g to 19 g in 117 s respectively, before experiencing a decline in the drainage rate. The test duration for foam with E = 13.1 was 498 s and 319 s for foam with E = 15.8.

b) Mass loss of foams at 40 kW/m^2

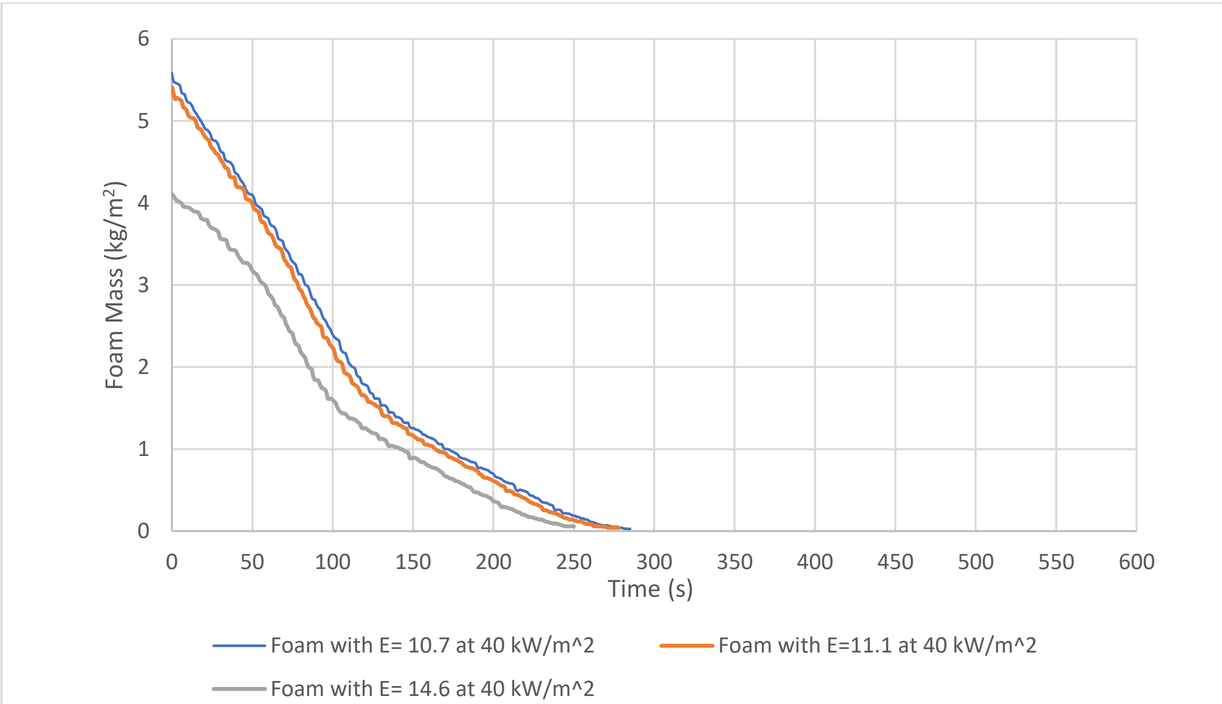

Figure 4.37 - Foam mass loss at heat flux of 40 kW/m^2

Figure 4.37 shows the disintegration of foams with E = 10.7, E = 11.1 and E = 14.6 when exposed to constant heat flux of 40 kW/m^2. The foam with E = 10.7 exhibited similar drainage pattern as the foam with E = 11.1 at the same imposed thermal radiation. The foam with E = 10.7 reduced from 55.9 g to half its mass in 90 s. After this period, the drainage rate began to decrease as the foam mass disintegrate at a lower rate. The test lasted for 285 s.

The foam with E = 11.1 depleted at a shorter period by losing 50% of its initial mass of 54.2 g in 86 s and completely disintegrated in 278 s. The foam with E = 14.6 disintegrated faster than the other two foams of lower expansion ratios. The foam reduced from 41.2 g to 20.6 g in 79 s and completely disintegrated in 244 s.

c) Mass loss of foams at 60 kW/m²

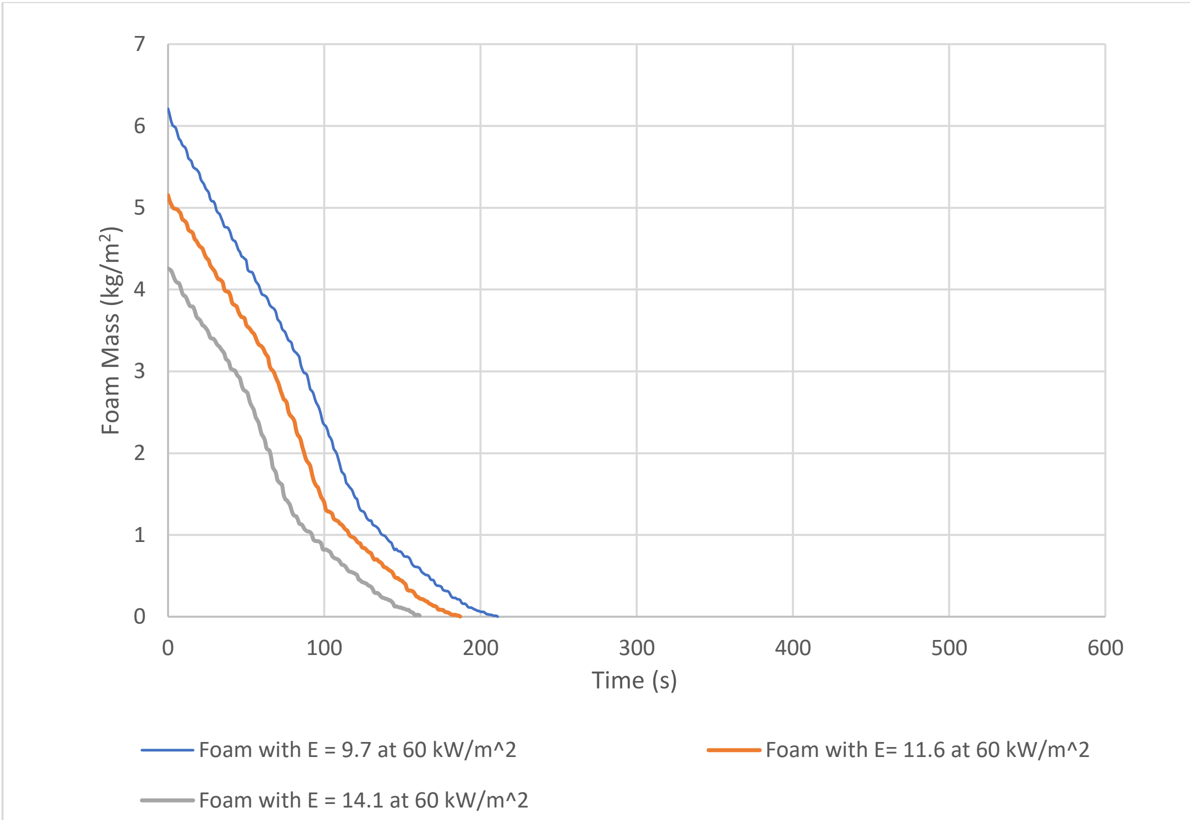

Figure 4.38 - Foam mass loss at heat flux of 60 kW/m^2

Figure 4.38 shows the disintegration of foams with E = 9.7, E = 11.6 and E = 14.1 when subjected to constant heat flux of 60 kW/m^2. The foam with E = 9.7 reduced from its initial mass of 62.1 g to half in 84 s and completely disintegrated in 211 s. Similarly, foam with E = 11.6 depleted at a shorter period by losing 50% of its initial mass of 51.6 g in 77 s and completely disintegrated in 187 s. The foam with E = 14.1 disintegrated faster than the other two foams of lower expansion ratios. The foam reduced from 42.7 g to 21.4 g in 62 s and completely disintegrated in 141 s. Overall, the mass loss of foams exposed to 60 kW/m^2 heat fluxes took place at a higher drainage rate within a short period than the foams subjected to heat fluxes of 20 kW/m^2 and 40 kW/m^2.

4.2.6 Time to half mass loss of foams

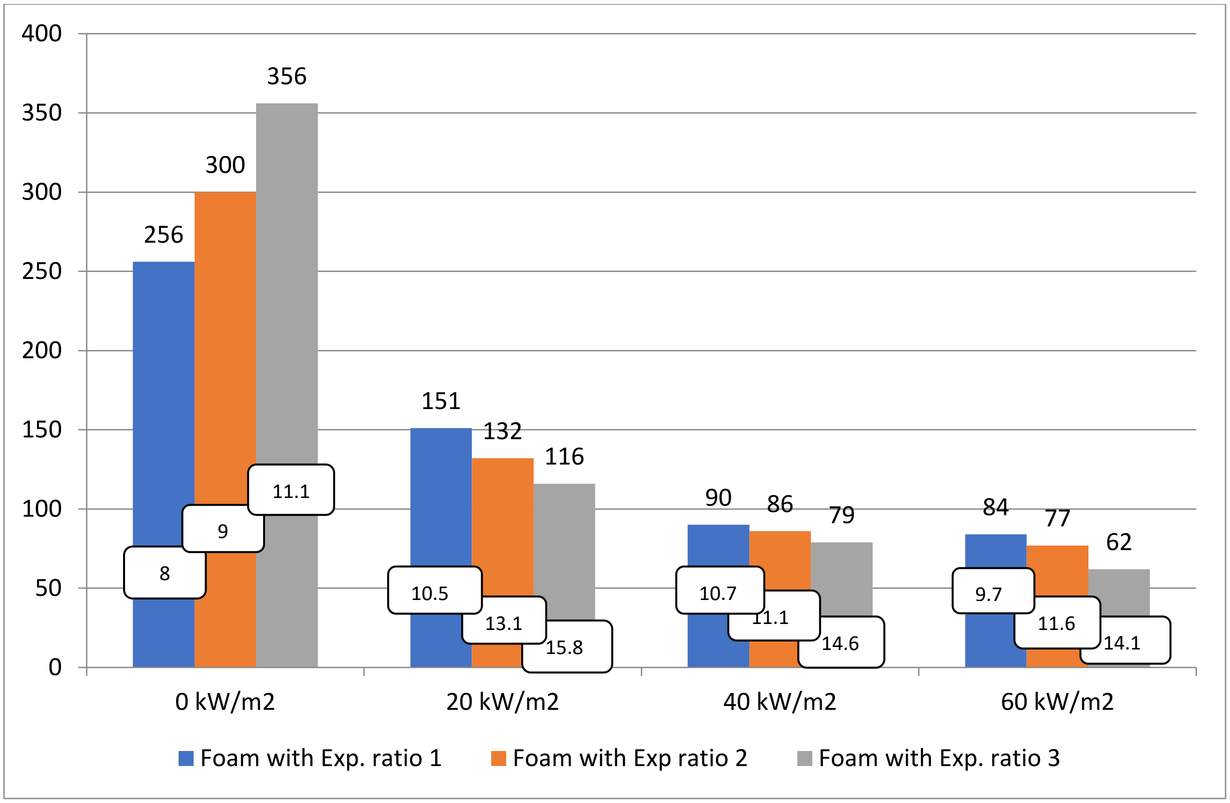

Figure 4.39 - Time to half mass loss of foams at different heat fluxes.

Figure 4.39 shows the time to half mass loss of foams at ambient temperature and imposed heat fluxes. At ambient temperature, the time for foams to reduce to half their initial masses increased as the foam expansion ratios increases. The result shows that free drainage took place at a faster rate in foams with low expansion ratios than foams with higher expansion ratio due to the percentage of solution content in them.

On the other hand, the time to half mass loss of foams when subjected to radiant heating decreased as the foam expansion ratio increases. Likewise, the time to half mass loss of foams decreased at higher irradiance level, resulting in faster drainage rate.

4.2.7 Experimental results on the drainage characteristics of the foam

Table 4.2 shows the summary of the test results conducted to investigate the drainage characteristics of the foam. It comprised of the weight of the foam, weight of the drained foam, mass of the evaporated foam and the test duration.

Table 4.2 - Summary of the Experimental Results

Test No	Heat Flux (kW/m^2)	Weight of Foam Sample (g)	V_{FS} (ml)	Expansion Ratio	Weight of drained foam (g)	Weight of Evaporated Foam (g)	Percentage of Evaporated Foam	Test Duration min:s
1	0	75	600	8	59.7	-		17:00
2	0	64	600	9.4	48.3	-		17:00
3	0	54	600	11.1	39.2	-		17:00
4	20	57.2	600	10.5	33.5	23.7	41.43	9:34
5	20	45.8	600	13.1	24.5	21.3	46.51	8:18
6	20	38.0	600	15.8	18.5	19.5	51.31	7:52
7	40	55.9	600	10.7	31.9	24.0	42.93	4:45
8	40	54.2	600	11.1	30.5	23.7	43.73	4:38
9	40	41.2	600	14.6	20.9	20.3	49.27	4:04
10	60	62.1	600	9.7	33.6	28.5	45.89	3:31
11	60	51.6	600	11.6	26.0	25.6	49.61	3:07
12	60	42.7	600	14.1	20.8	21.9	51.29	2:41

To determine the expansion ratio of the foams used, the following calculation was made;

For test 4, Weight of foam in the test pan = 57.2 g

Density of foam solution = 1 g/ml

Volume of foam solution = $\frac{weight\ of\ foam}{Density} = \frac{57.2}{1}$ = <u>57.2 ml</u>

Volume of expanded foam to fill the test pan, V_{FS} = 100 x 100 x 60 = 600,000 mm^3 = 600 ml

Expansion ratio = $\frac{Volume\ of\ \ expanded\ foam}{Volume\ of\ foam\ solution} = \frac{600}{57.2}$ = 10.5

The scale has an accuracy of 0.5 g

Percentage accuracy = $\frac{0.5}{57.2}\ x\ 100\ = 0.87\ \%$

4.2.8 Percentage of Evaporated Foam

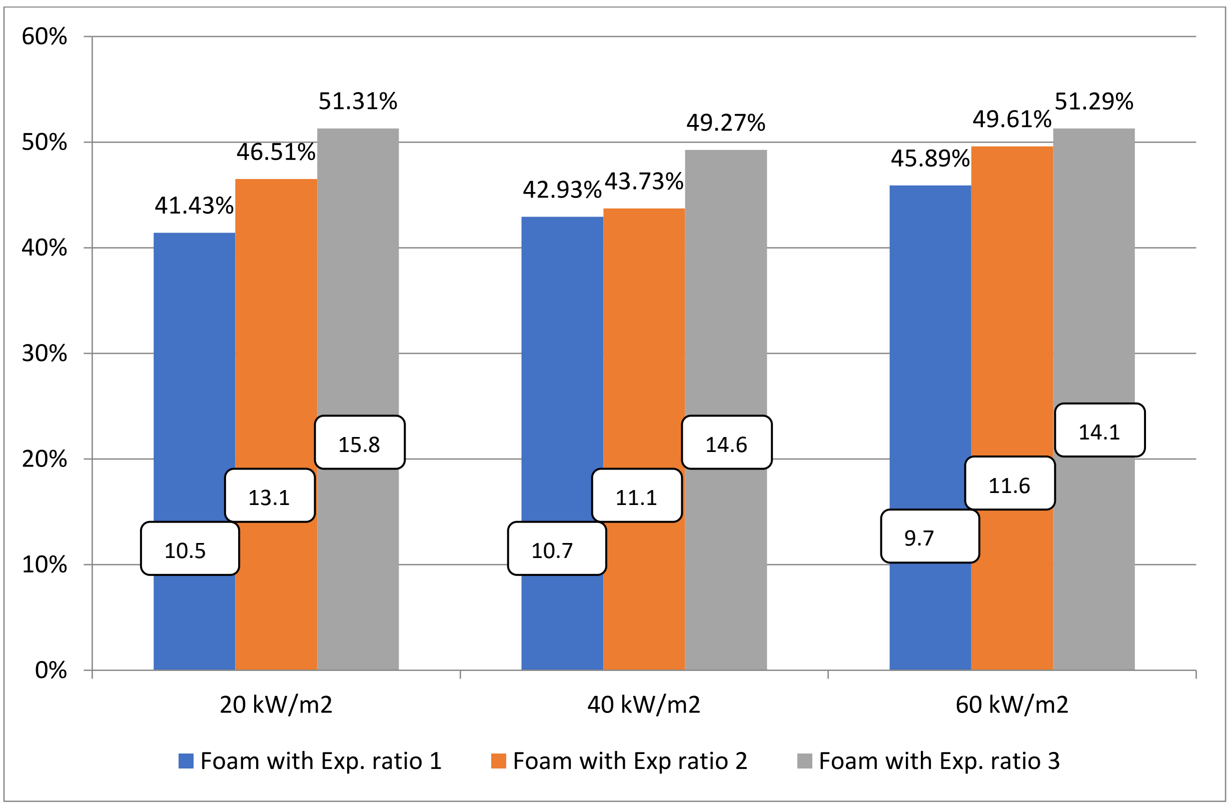

Figure 4.40 - Percentage of evaporated foam at different imposed heat flux

Figure 4.40 shows the percentage of evaporated foams at different imposed heat flux. The percentage of evaporated foam was greater in foams with higher expansion ratio when exposed to the same irradiance level. Consequently, the duration for the foam mass loss decreased with increase in expansion ratio and imposed thermal radiation. Overall, the observations made in this study on the temperature profile of foams, mass loss rate of foams and the drainage rate were similar to the studies conducted by Lattimer [31], Persson [20], Isaksson and Persson [21].

4.3 Fire Suppression Tests

The effectiveness of using a 3 L portable extinguisher to suppress gasoline pool fires and wood crib fires were investigated. Based on the results of the tests discussed in the previous sections, the following set-up was used:

- A 3 % foam solution in conjunction with the 2-m hose length was used to generate the foam because of the foam's consistency and drainage characteristics under heat fluxes.
- Two discharge methods were used for the pool fire tests and the use of tube with gun nozzle was used for the wood crib fire due to its good discharge characteristics.

4.3.1 Pool Fire Tests

The extinguishing performance of the portable CAF system on both 0.23-m^2 and 0.47-m^2 pool fires were investigated. The test results for the gasoline pool fire tests are shown in Table 4.3. Figure 4.41 (a-d) shows the pictures taken at different times during one of the 0.23-m^2 pool fire tests.

(b) Time: 0 s

(b) Time: 20 s

(c) Time: 35 s

(d) Time: 48 s

Figure 4.41 (a-d) - Suppression of the 0.23-m^2 pool fire at different times

Table 4.3 - Results of Pool Fire Tests

Test No	Fire Size m^2	Nozzle type	Pre-burn time min:s	Application time to suppress, min:s	Application time to extinguish, min:s
1	0.23	Tube	0:12	0:35	0:48
2	0.23	Tube	0:11	0:33	0:45
3	0.23	Tube	0:13	0:39	0:51
4	0.23	Tube	0:11	0:35	0:44
5	0.46	Tube	0:09	0:45	1:01
6	0.46	Tube	0:08	1:05	1:18
7	0.46	Gun	0:13	0:51	1:00

For the 0.23-m^2 pool fire, 1.1 litres of gasoline were poured into the test pan and ignited. A pre-burn time of about 12 s was allowed for the fire to reached fully developed phase. The portable CAF system was manually activated, and the foam was discharged continuously against the wall of the test pan. Fire suppression was observed as the foam spread over the burning surface. For the first test, the fire was controlled at 35 s, after the foam had covered about 90% of the burning surface. Full extinguishment was achieved in 48 s as no re-ignition was observed. Overall, the 0.23-m^2 pool fires were fully extinguished in less than 1 min for all the four tests. The fires were extinguished in 48 s, 45 s, 51 s and 44 s, respectively.

The 0.46-m^2 pool fire reached fully developed phase at a fast rate with high heat intensity. The pre-burn time for the fifth test was about 9 s before activating fire suppression. It took a longer time for the foam blanket to cover the large burning surface area. The fire was controlled at 45 s after large portion of the burning surface was covered and fully extinguished after 61 s. However, the wind affected the extinguishment time for the other two tests. The wind speed increased during the test thereby making it difficult for the foam to reach the seat of the fire. The suppression time was longer and subsequently the extinguishment time. Overall, the use of tube with gun nozzle in place of the tube nozzle reduced the extinguishment time.

4.3.2 Wood Crib Fire Tests

The extinguishing performance of the portable CAF system on wood crib fires was investigated using wood cribs of 8 layers and 12 layers constructed using fir lumber. Each layer comprised of 6 members of fir lumber. The foam was created from a 3% foam solution and developed inside a 2-m hose length and later discharged via tube-gun nozzle for quick suppression.

a) 8 layers wood crib

Figure 4.42 (a-f) shows pictures taken during the test, comprising of the wood crib construction, ignition source, fully developed phase, control and total extinguishment of the fire.

(a) Wood Crib Construction

(b) Ignition of fuel in the test pan

(c) Fully developed phase

(d) Suppression of the fire

(e) Control of the fire

(f) Total extinguishment of the fire

Figure 4.42 (a-f) – 8 layers wood crib fire test

8-layers of evenly arranged wood crib were constructed as shown in Figure 4.42 (a) for the test. Each layer of the wood crib comprised of 6 fir lumber sticks with dimensions of 38 mm x 38 mm x 635 mm. The ignition source of 800 ml gasoline was ignited, and the wood crib was allowed to burn as shown in Figure 4.42 (b) until the ignition source was exhausted. During this period, the wood crib had reached fully developed burning phase as shown in Figure 4.42 (c). The pre-burn time, which refers to the duration from initiating the ignition source to commencement of fire suppression, was 3 min 50 s. Fire suppression was activated with the application of foam in both vertical and horizontal direction on the entire burning surface. Likewise, the foam was discharged directly into the hollow spaces in the wood crib as shown in Figure 4.42 (d).

The fire was controlled at 1 min 5 s but there was a lot of smoke emerging from the crib that could re-ignite the fire as shown in Figure 4.42 (e). The fire was completely extinguished after 1 min 35 s of continuous foam application. The wood crib was covered with foam as shown in Figure 4.42 (f). The test was repeated twice with similar results. As it can be seen from the pictures, there was some wind played during the tests which promoted re-ignition. It is expected that performing the tests indoor would result in shorter extinguishing times.

b) 12 layers wood crib

Figure 4.43 (a-f) shows pictures taken during the test, comprising of the ignition source, burning of the wood crib, wind effect on the burning, fully developed phase, suppression and control of the fire. 12-layers comprising of 6 fir lumber sticks with dimensions of 38 mm x 38 mm x 500 mm were used. The ignition source of 1100 ml gasoline was ignited, and the wood crib was allowed to burn as shown in Figure 4.43 (a-b) until extinguishment of the ignition source. During this period, the wood crib had reached fully developed burning phase as shown in Figure 4.43 (c). The pre-burn time, which refers to the duration from ignition of the source to commencement of the fire suppression, was 4 min 43 s.

(a) Ignition of fuel in the test pan (b) Burning of the wood crib

(c) Effect of wind on the test (d) Fully developed phase

(e) Suppression of the wood crib fire

(f) Fire was controlled but not extinguished

Figure 4.43 (a-f) – 12 layers wood crib fire test

The fire suppression technique was similar to the previous test. The system was charged with 2L of 3% foam solution and applied under pressure. The fire was partially suppressed as the foam was discharged into the hollow spaces within the wood crib as shown in Figure 4.43 (e). However, the wind affected the suppression time by adding more air to the chemical reaction as shown in Figure 4.43 (d). The first application time lasted for 2 min 20 s before the extinguisher was refilled and re-activated after 40 s. During this period, the burning increased as the foam on the burning surface evaporated. The fire was controlled during the second application, but it was not extinguished as shown in Figure 4.43 (f). Overall, the test lasted for 13 min 37 s while the total application time and recharge time as 7 min 54 s.

For the second test, the system was charged with 3 L of 3 % foam solution and applied under pressure. The pre-burn time for the wood crib to reach fully developed phase was 3 min 50 s. The fire was suppressed to a lower intensity than the first test at this stage with application time of 3 min 1 s. The fire was fully controlled during the second application as the burning continued at a smoldering state before the crib collapsed. The test lasted for 10 min and 53 s with a total application time of 7 min 3 s. The test was repeated twice without attaining total extinguishment of the fire. Overall, the wind had a negative effect on extinguishing wood crib fires by adding more air to the burning surface and causing re-ignition

5 CONCLUSIONS AND RECOMMENDATIONS

The aim of this research was to investigate the discharge characteristics of a portable compressed air foam system, fire suppression performance of the system and drainage characteristics of the foam. Series of tests were conducted to ascertain the results under various operating conditions.

5.1 Conclusions

5.1.1 Discharge Characteristics of a Portable CAF System

The experiment investigated the effect of air pressure on expansion ratio, discharge range of the foam and foam flow rate as a function of pressure. Based on the results and observations, the following conclusions can be made:

1) The foams generated from 3 % and 4 % foam solution were partially developed inside the 1-m hose leading to increase in expansion ratio as the pressure increases whereas the same solutions for both 2-m and 3-m hose lengths generated fully developed foams inside the hose.
2) The 3% and 4% foam solution for 1-m hose length generated wet foams with low expansion ratio in the ranges of 8 and 15. Similarly, 2% solution for the 2-m hose length generated wet foam with low expansion ratio ranging from 6 to 8.
3) The 3% and 4% foam solution for both 2-m and 3-m hose lengths generated fluid foams with medium expansion ratio in the ranges of 19 and 28. However, the solutions for the 3-m hose length generated higher foam expansion ratios than the 2-m hose length for all pressures.
4) The discharge range test results showed longer projection at higher momentum in the 2-m and 3-m hose as compared to the 1-m hose. Likewise, the portable system could generate

uniform and consistent foam at low pressures when the foam was fully developed inside the hose before discharge.

5) The test results on flow rate showed that when the portable system is operated at a low rate, its application time increases providing more time for fire suppression and heat exposure protection without altering the consistency of the foam. Overall, all the tested foams met the requirements of the CAN/ULC-S508 standard.

5.1.2 Drainage Tests

The response of the foam to heat and mass loss of foam were investigated in relation to the expansion ratio and imposed thermal radiation. Constant thermal radiation in the ranges of 0 - 60 kW/m^2 was imposed on the foam during the tests.

1) The drainage rates of foams with no imposed heat depend on the foam expansion ratio. The test results for the free drainage of foams showed higher drainage rate in foams with low expansion ratio due to the percentage of their water content. Overall, all the tested foams exhibited similar drainage pattern, in terms of foam mass loss, but at different drainage rates. As the foam expansion ratio increased, the time required for the foam to lose half its mass and the percentage of dry foam increased.
2) Foams exposed to thermal radiation showed similar trend of temperature profile but disintegrated at different drainage rates. High drainage rate was observed in foams with higher expansion ratio at the same or higher irradiance level. Similarly, the percentage of evaporated foam and mass loss rate was greater in foams with higher expansion ratio when exposed to the same or higher irradiance level. However, the time to half mass loss decreased with increase in foam expansion ratio and heat flux.

3) The mass loss rate of foams increased with increasing irradiance level. The average mass loss rate of foams when exposed to 20 kW/m^2, 40 kW/m^2 and 60 kW/m^2 were 0.02 $kg/s.m^2$, 0.035 $kg/s.m^2$and 0.05 $kg/s.m^2$ respectively.

5.1.3 Fire Suppression Tests

Pool fire tests and wood crib fire tests were conducted to determine the fire suppression capability of the portable CAF system. From the experimental results, the following conclusions are made:

1) Portable CAF system with a 2-L capacity is capable of extinguishing the 0.23 m^2 fire and 0.46 m^2 pool fires.
2) The extinguishment time for the pool fires was a function of the type of nozzle used and the wind condition. The gun nozzle provided faster knockdown of the fire than the tube as the nozzle generated sufficient momentum that could penetrate the fire plume within a short duration
3) The portable CAF system is effective at controlling and extinguishing wood crib fires. The system controlled the 8 layers wood crib fire in 1 min 5 s and completely extinguished it in 1 min 35 s. Total extinguishment was not attainable for the 12 layers wood crib fire. However, this may be possible in an enclosed space.

5.2 Recommendations to future work

1) The test results on the discharge characteristics of foams were obtained by using only two discharge methods. Therefore, it is recommended in future studies to investigate the effect of different discharge methods on the discharge properties of foam at different pressures.
2) In order to properly investigate the extinguishing capability of the portable CAF system, it is recommended to conduct the pool fire tests and wood crib tests in an enclosed space with no interference of wind.

3) In this research, foam expansion ratios in the ranges of 9.7 to 15.8 were used to investigate the drainage characteristics of foam. It is recommended to investigate the drainage characteristics of foam with wider range of expansion ratios by using a system that could generate foams with higher expansion ratios.
4) The apparatus used for the drainage test could only accommodate foam in the test pan, it would be beneficial to also investigate the time to ignition of fuel when covered with a foam layer in future research.

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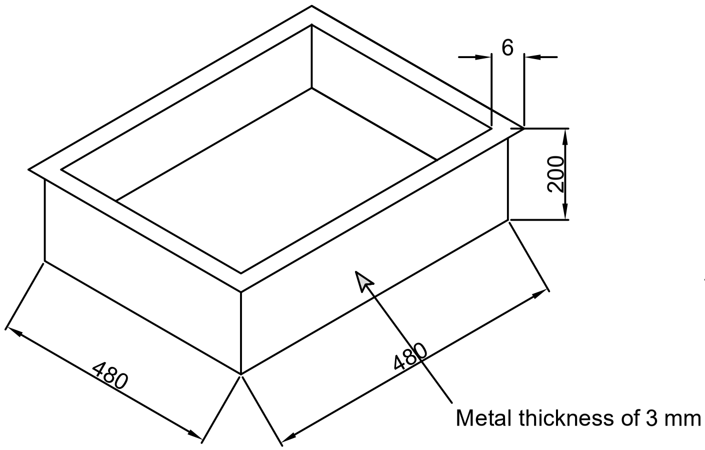
Appendix A



Pan Size for rating 1-B
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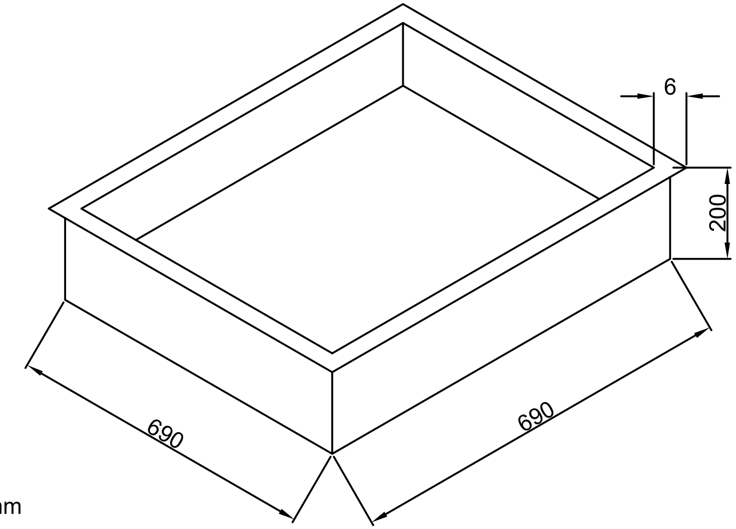

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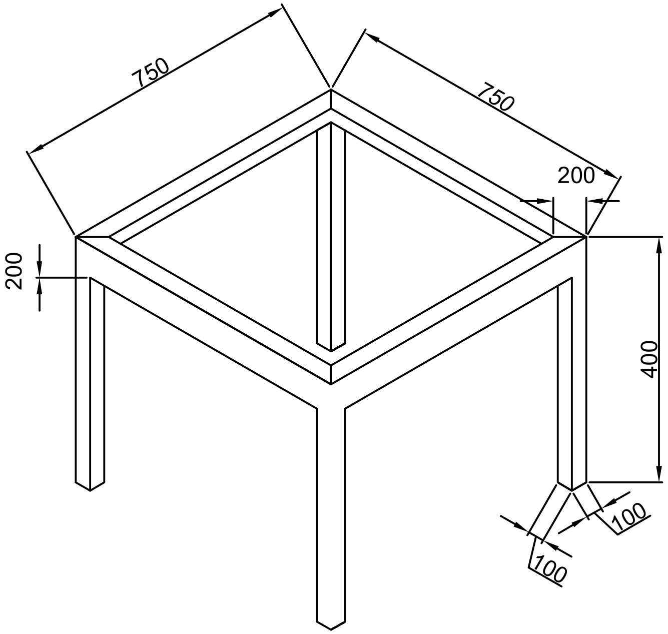
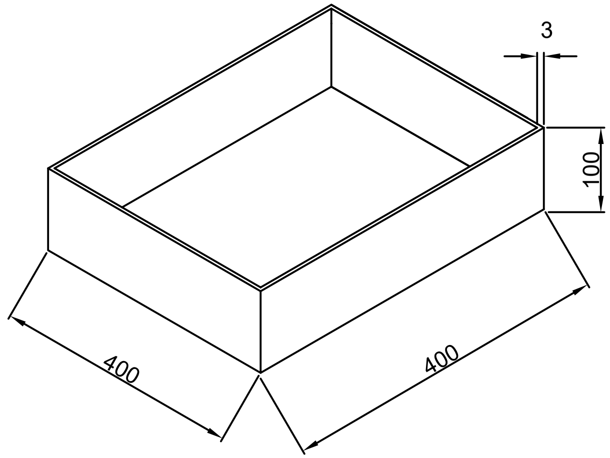


Steel Support Frame



Ignition Pan
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