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NAME OF SUPERVISOR/NOM DU DIRECTEUR DE THÈSE E. G. PLETT

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THERMAL ANALYSIS OF A CYLINDRICAL PARABOLIC
SOLAR COLLECTOR FOR DIFFERENT TYPES OF
ABSORBER PIPES

by

A.E. CARAPANAYOTIS, Dipl. Mech. and El. Eng.

A thesis submitted to the Faculty of Graduate
Studies in partial fulfillment of the
requirements for the degree of

Master of Engineering

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Carleton University
Ottawa, Canada

September 11, 1981

The undersigned recommend to the Faculty of Graduate
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"THERMAL ANALYSIS OF A CYLINDRICAL PARABOLIC SOLAR
COLLECTOR FOR DIFFERENT TYPES OF ABSORBER PIPES"

by A.E. CARAPANAYOTIS, in partial fulfillment of the requirements
for the degree of

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Thesis Supervisor

Chairman, Department of
Mechanical and Aeronautical
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ABSTRACT

This report has concentrated on the thermal analysis of various absorbers that may be incorporated on a concentrating collector to be used for medium temperature applications. The absorber configurations under consideration were divided into two classes: one using liquids as the working fluids and one using air. Two types of liquid absorbers were considered: (a) an absorber consisting of a metallic receiver pipe with selective surface and one or two glass covers and (b) an absorber using a black liquid as the receiver and one or two glass covers. The air collector was considered to consist of two glass covers. Inside the inner one, there were small metallic spheres in the form of a packed bed serving as the receiver.

The effect of pressure on cylindrical (annular) enclosed spaces was analyzed to determine the extent of the usefulness of a vacuum space around the receiver. Thus, vacuum losses due to poor sealing were found to cause an appreciable degradation of efficiency.

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NOMENCLATUREEnglish Letters

a	aperture of the cylindrical parabolic collector, thermal diffusivity
A_i	area of surface i
C_p	specific heat
D	diameter
d_p	particle diameter
E	emissive power of a surface
f	focal length of the parabolic reflector
g	acceleration of gravity
$F_{i \rightarrow j}$	configuration factor between surfaces i and j
F_{opt}	optical intercept factor
G_o	mass flow rate per unit cross-sectional area
G	irradiation
Gr	Grashof Number $(\frac{g \beta \Delta T L^3}{\nu^2})$
h	heat transfer coefficient
I_D	intensity of direct solar energy
J_i	radiosity of surface i
J_{iD}	diffuse radiosity of surface i
l	length of the absorber
L	length
Nu	Nusselt Number $(\frac{h L}{k})$
P	pressure
Pr	Prandtl Number (ν/a)
$q_{i \rightarrow j}$	radiation exchange between surfaces i and j
q	heat flux
R	resistance

NOMENCLATURE (cont'd)

Re	Reynolds Number ($u_o L/\nu$)
SRI	solar radiation directed toward the receiver pipe
T	temperature
u_o	velocity
$\dot{V}$	volume flow rate
w	velocity of the wind
x	horizontal coordinate
y	horizontal coordinate
z	vertical coordinate

Greek Letters:

α_i	absorptance of surface i for solar radiation
α_i'	absorptance of surface i for the long wavelength radiation
β	volume expansion coefficient, proportionality constant
Δx	a segment of the absorber
δ	thickness of evacuated space
ϵ_i	emittance of surface i for solar radiation
ϵ_i'	emittance of surface i for the long wavelength radiation
η_{th}	thermal efficiency
θ	angle
κ	conductivity
λ_m	mean free path
μ	viscosity
ν	kinematic viscosity

XII

NOMENCLATURE (cont'd)

ξ	proportionality factor
ρ	density
ρ_r	reflectance of reflector surface
ρ_{iD}	diffuse component of reflectance of surface i for the long wavelength radiation
ρ_{iS}	specular component of reflectance of surface i for the long wavelength radiation
ρ_i	reflectance of surface i for solar radiation
ρ_i	reflectance of surface i for long wavelength radiation
σ	Stefan-Boltzmann's constant
σ	standard deviation
τ_i	transmittance of surface i for solar radiation
τ_i	transmittance of surface i for the long wavelength radiation
τ_{iD}	diffuse component of transmittance of surface i for the long wavelength radiation
τ_{iS}	specular component of transmittance of surface i for the long wavelength radiation
ϕ	half rim angle of the parabolic collector
ψ_i	angle
ψ	distance

Subscripts and Indices:

a	ambient
c	convection, critical value
cc	conduction-convection
D	diffuse component

NOMENCLATURE (cont'd)

env	environment
eq	equivalent
f	fluid
g	gas
in	inlet conditions
l	long wavelength region
m	mean value
out	outlet conditions
p	particle
r	reflector
s	specular
u	useful
w	wall

CHAPTER 1

INTRODUCTION

In the last thirty years, the study of solar energy conversion has concentrated on applications which do not require excessively high temperatures (such as would be required in power generation). For low temperature applications, the flat plate collectors are mostly used while the concentrating collectors are reserved for medium and high temperature applications.

The study undertaken in this report describes the thermal analysis of a concentrating collector for different types of absorber pipes at medium operating temperatures. An essential first thing was calculation of the optical intercept factor in order to determine how much of the solar radiation incident on the reflector is directed towards the receiver pipe.

The effect of pressure on heat transfer in cylindrical (annular) enclosed spaces was analyzed to determine how useful a vacuum space around the receiver is and the effects of vacuum losses on the efficiency. Problems of sealing in configurations consisting of a single glass cover and the solution of these problems by using a double glass cover configuration were considered and compared using the effects of vacuum mentioned above.

Recent literature gives experimental results of thermal efficiencies of configurations using a black liquid in a glass tube as the heat transfer medium. In this report, a thermal analysis of configurations using both a single and a double glass cover was undertaken. These configurations have been projected to be less costly than configurations which consist of metallic receivers since metallic receivers with selective surfaces have proven to be very costly and have shorter lifetimes.

In most of the literature relating to this topic, configurations which use liquid transfer media are analyzed. In this report, the thermal analysis of a configuration which uses air as the heat transfer medium was carried out as well. This finds various industrial applications such as in drying.

It is expected that comparison of the performance of different types of absorber pipes will be used to determine which of them is preferable for particular applications and environmental conditions.

CHAPTER 2

OPTICAL ANALYSIS OF THE COLLECTOR

2.1 The Collector

The collector is a cylindrical concentrator with parabolic cross-section which focuses on a line coincident with the center-line of the absorber pipe. The beam radiation will focus on the absorber pipe if the sun is in the central plane of the concentrator, that is, the plane including the focal axis and the vertex line of the reflector (see Fig. 2.1). The equation of the parabolic section is defined by the formula

$$y^2 = 4fz \quad (2.1)$$

The following terminology will be used throughout this section: the word 'collector' will denote the whole system whose main parts are the reflector or concentrator and the absorber pipe. The 'reflector' is the part of the collector which reflects the solar radiation and directs it onto the absorber pipe. The 'absorber pipe' consists of the receiver pipe and one or two glass covers. The receiver pipe absorbs the solar radiation and transfers it to the working fluid as thermal energy. The 'glass covers' are used to reduce the radiation losses to the surroundings (greenhouse effect) and also to reduce the conduction-convection losses to the surroundings by keeping the air trapped between them at a very low pressure.

2.2 Optical Intercept Factor (F_{opt})

The beam solar radiation coming directly from the sun is reflected by the reflector and is focussed on the receiver tube. Even if the solar radiation is parallel to the central plane, which means zero tracking error, the radiation arriving at the receiver tube is less than the radiation leaving (reflected by) the reflector. There are two reasons for this:

- a) The incident beam solar radiation has an angular width of $32'$ (0.53°).
- b) The surface of the reflector is not a perfect parabola.

Analysis and calculation of the optical intercept factor (F_{opt}) will follow. F_{opt} is defined as:

$$F_{opt} = \frac{\text{beam radiation arriving at the receiver tube}}{\text{beam radiation reflected by the reflector}}$$

Fig. 2.2 shows the relationship for a segment of the reflector surface. The nominal ray (S-0) coming from the center of the sun is reflected by the ideal reflector surface and arrives at the center of the receiver pipe (0-i). The random ray from the sun (e-0) (with angular distance ψ_2 from the nominal) is reflected by the ideal reflector surface and directed towards the receiver pipe with angular distance ψ_2 (0-b)^[1].

Actually, as has already been mentioned, the surface of the reflector is not ideal and by assuming that the reflector has an angular deviation ψ_1 from the ideal, all the rays reflected by the real surface will intercept the receiver tube with an angle $2\psi_1$ [angle between (0-i) and (0-c)].

The distance ψ from the center of the receiver tube (i-g) is:

$$\psi = r \sin(2\psi_1 + \psi_2) \approx r(2\psi_1 + \psi_2) \quad (2.2)$$

The distance r from the reflector to the center of the receiver tube (0-i) is:

$$r = \frac{a(1+\cos\phi)}{2\sin\phi(1+\cos\theta)} \quad (2.3)$$

where (see figure 2.3)

ϕ - half rim angle

θ - angle between optical axis and nominal reflected ray

a - aperture.

From Eqns. (2.2) and (2.3),

$$\psi = \frac{a(1+\cos\phi)(2\psi_1 + \psi_2)}{2\sin\phi(1+\cos\theta)} = \kappa(2\psi_1 + \psi_2) \quad (2.4)$$

where

$$\kappa = \frac{a(1+\cos\phi)}{2\sin\phi(1+\cos\theta)}$$

It is assumed that the variables ψ_1 and ψ_2 are normally distributed with a mean value of zero and variances $\sigma_{\psi_1}^2$ and $\sigma_{\psi_2}^2$ respectively [1].

$$\psi_1 = \frac{1}{\sqrt{2\pi}} \exp \left[-\frac{1}{2} \sigma_{\psi_1}^2 \right] \quad (2.5)$$

$$\psi_2 = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{1}{2} \sigma_{\psi_2}^2\right] \quad (2.6)$$

The variance σ_{ψ}^2 of the intercept point ψ is given as [1]:

$$\sigma_{\psi}^2 = \frac{a^2 (1+\cos\phi)^2 (4\sigma_{\psi_1}^2 + \sigma_{\psi_2}^2)}{4\sin^2\phi (1+\cos\theta)^2} \quad (2.7)$$

and the average variance over all values of θ between ϕ and $-\phi$ is

$$\bar{\sigma}_{\psi}^2 = \frac{a^2 (1+\cos\phi)^2 (4\sigma_{\psi_1}^2 + \sigma_{\psi_2}^2)}{4\sin^2\phi} \cdot \frac{1}{2\phi} \int_{-\phi}^{\phi} \frac{d\theta}{(1+\cos\theta)^2}$$

Evaluating the integral gives:

$$\begin{aligned} \int_{-\phi}^{\phi} \frac{d\theta}{(1+\cos\theta)^2} &= 2 \left[\frac{1}{2} \frac{\sin\theta}{(1+\cos\theta)} + \frac{1}{6} \frac{\sin^3\theta}{(1+\cos\theta)^3} \right]_{-\phi}^{\phi} \\ &= \frac{2}{3} \frac{\sin\phi (2+\cos\phi)}{(1+\cos\phi)^2} \end{aligned}$$

and finally

$$\bar{\sigma}_{\psi}^2 = \frac{a^2 (4\sigma_{\psi_1}^2 + \sigma_{\psi_2}^2) (2+\cos\phi)}{12\phi \sin\phi} \quad (2.8)$$

For the closed interval $[-\frac{D_r}{2}, \frac{D_r}{2}]$ where D_r is the receiver diameter, the optical intercept factor (F_{opt}) is given by the expression [1]

$$F_{opt} = \frac{1}{\bar{\sigma}_{\psi} \sqrt{2\pi}} \int_{-\frac{D_r}{2}}^{\frac{D_r}{2}} \exp\left[-\frac{1}{2} \left(\frac{\psi}{\bar{\sigma}_{\psi}}\right)^2\right] d\psi \quad (2.9)$$

By introducing the variable $z = \frac{\psi}{\sigma_\psi}$ and using limits from $-\frac{D_r}{2\sigma_\psi}$ to $\frac{D_r}{2\sigma_\psi}$

$$F_{\text{opt}} = \frac{1}{\sqrt{2\pi}} \int_{-\frac{D_r}{2\sigma_\psi}}^{\frac{D_r}{2\sigma_\psi}} \exp\left[-\frac{z^2}{2}\right] dz = \left[\text{erf}\left(\frac{z}{\sqrt{2}}\right)\right]_{-\frac{D_r}{2\sigma_\psi}}^{\frac{D_r}{2\sigma_\psi}} \quad (2.10)$$

The error function can be calculated analytically using the formula [2]

$$\text{erf}\left[\frac{z}{\sqrt{2}}\right] = \frac{2}{\sqrt{\pi}} \exp\left(-\frac{z^2}{2}\right) \sum_{n=0}^{\infty} \frac{2^n \left(\frac{z}{\sqrt{2}}\right)^{2n+1}}{1.3 \dots (2n+1)} \quad (2.11)$$

The variation of the optical intercept factor as a function of the half rim angle and the diameter of the receiver for various apertures and variances of the reflector surface ($\sigma_{\psi_1}^2$) has been calculated using the computer program which is listed in Appendix 1. The results are summarized in Figs. 2.4 to 2.6. It may be observed that:

- For high σ_{ψ_1} (imperfect parabola), a big receiver diameter is needed to obtain a high intercept factor which results in high thermal losses.
- For big apertures, a bigger receiver diameter is also needed.
- For increasing rim angles, the optical intercept factor increases (for fixed receiver diameter).

Fig. 2.1 The Collector

- o-s Ray from the center of the sun
- o-e Random ray from sun
- o-i Reflected ray from ideal reflector surface
- o-b Reflected random ray
- o-c Reflected ray from the center of the sun for real reflector surface
- o-a Reflected random ray from real reflector surface

Figure 2.2 Schematic diagram for optical analysis of the collector.

Figure 2.3 Schematic diagram of the cross section of the parabolic collector showing ψ , θ , a .

Fig. 2.4 Optical intercept factor Vs half rim angle ($a=1$ m)

Fig. 2.5 Optical intercent factor Vs half rim angle ($a=1.5 \text{ m}$)

Fig. 2.6 Optical intercept factor Vs half rim angle ($a=2$ m)

CHAPTER 3

VARIATION OF HEAT TRANSFER LOSSES AS A FUNCTION
OF PRESSURE IN CYLINDRICAL ENCLOSED SPACES

In any configuration of absorber pipe, an evacuated space is needed over the receiver tube to minimize the conduction-convection losses to the surroundings. It is very important, therefore, to analyze the heat transfer in cylindrically enclosed spaces containing air for various values of pressure

Fig. 3.1 shows how the fluid circulates in a horizontal cylindrical space if the temperature of the inner surface is higher than that of the outer one (T_1 and T_2 respectively). Circulation occurs only above the lower edge of the heated surface, the fluid below it remaining stagnant.

The heat transfer from the inner to the outer surface takes place by a very complicated process of heat transfer by free convection and conduction.

In practice, this situation is substituted for by an equivalent which uses the formula of pure conduction for a flat layer: [3]

$$q = \frac{\kappa_{eq}}{\delta} (T_1 - T_2) \quad (3.1)$$

where q is the mean rate of heat transfer, δ is the thickness of the enclosed space and κ_{eq} is the equivalent thermal conductivity which accounts for both free convection and conduction.

The quantity $\beta_c = \frac{\kappa_{eq}}{\kappa}$ where κ is the thermal conductivity of the fluid is the effect of the free convection and depends on the Gr Pr term.

The Grashof and the Prandtl numbers are calculated by using the thickness of the enclosed space as the characteristic length and the mean fluid temperature $T_f = \frac{T_1 + T_2}{2}$ as the reference temperature.

The following experimental correlations describe the quantity β_c [3]:

$$\text{At } 10^3 < \text{Gr Pr} < 10^6, \quad \beta_c = 0.105(\text{Gr Pr})^{0.3} \quad (3.2)$$

$$\text{At } 10^6 < \text{Gr Pr} < 10^{10}, \quad \beta_c = 0.40(\text{Gr Pr})^{0.2} \quad (3.3)$$

The above two formulae are approximated by:

$$\text{At } \text{Gr Pr} > 10^3, \quad \beta_c = 0.18(\text{Gr Pr})^{1/4} \quad (3.4)$$

For small values of $\text{Gr Pr} < 10^3$, $\beta_c = 1$ or $\kappa_{eq} = \kappa$. This means that the heat transfer is by pure conduction and the effect of free convection is negligible.

For fluid temperatures in the range $250\text{K} \leq T_f \leq 500\text{K}$ and pressure range $0.01 \text{ atm} \leq P \leq 1 \text{ atm}$, an analytic expression for the product Gr Pr for air is: [4]

$$\text{Gr Pr} = 2737(1+2b)^2 b^4 \Delta T (1008)^3 P^2 \quad (3.5)$$

where

$$b = 100/T_f$$

In this formula, T_f is in K, ΔT is in K or $^{\circ}\text{C}$, δ is in meters and P is in atm.

Also, the thermal conductivity of air may be calculated from the formula [4]:

$$\kappa = 0.002528 T_f^{3/2} / (T_f + 200) \quad \text{W/m K} \quad (3.6)$$

where T_f is in K. This formula is valid for the pressure range $0.01 \text{ atm} < P < 1 \text{ atm}$ with δ greater than 1mm.

From Eqn. (3.5) using the value $\text{Gr Pr} = 1000$, the critical pressure P_c below which the heat transfer is by pure conduction, is calculated as:

$$P_c = 1 / [2.737(1+2b)^2 b^4 \Delta T (100\delta)^3]^{1/2} \quad (3.7)$$

Below P_c the heat transfer is calculated using the Fourier formula:

$$q = \frac{\kappa}{\delta} (T_1 - T_2) \quad (3.8)$$

The conductivity of most gases is independent of the pressure if the molecular mean free path (λ_m) is much less than the heat transfer length (δ). Therefore, for several decades of pressure below the critical (P_c), the rate of heat transfer is independent of pressure.

The mean free path λ_m for air between 100K and 1900K is given in [1] as:

$$\lambda_m = \frac{552.11 \times 10^{-12} T_f^2}{(1.8 T_f + 198.6) P} \quad (3.9)$$

where

$$\lambda_m [=] \text{ m}$$

$$T_f [=] \text{ K}$$

$$P [=] \text{ atm}$$

For pressures below the region of pure conduction, the rate of heat transfer is given by: [1]

$$q = \frac{\kappa}{(\delta + 2\lambda_m)} (T_1 - T_2) \quad (3.10)$$

where κ is the thermal conductivity of air at one atmosphere.

Fig. 3.2 shows the variation of heat losses as a function of the pressure and thickness of the evacuated space for fixed outer and inner surface temperatures. In the region of pressure between 1.0 and 10^{-1} atmospheres, the heat transfer is by both free convection and conduction. The energy losses at a pressure of 10^{-1} atms. drop to 80% and 40% ($\delta = 1\text{cm}$ and $\delta = 2\text{cm}$ respectively) of the losses at atmospheric pressure. In the region of pressures between 10^{-1} and 10^{-4} , the heat transfer is by pure conduction and the thermal conductivity is constant (hence no appreciable variation in heat losses across this range). At pressures below 10^{-4} atms, the heat losses drop rapidly because the mean free path of the gas particles start being comparable to the thickness of the evacuated space. At pressures below 10^{-6} atms, the heat losses are nil.

Figure 3.1 Free convection in the enclosed space between concentric cylinders.

Fig. 3-2 Heat transfer in the enclosed space between concentric cylinders as a function of a pressure

CHAPTER 4 .

THERMAL ANALYSIS OF THE FIRST CONFIGURATION

4.1 Thermal Analysis of the First Configuration with One Glass Cover4.1.1 Energy Balance

In the first configuration, the absorber pipe consists of the receiver tube which is a metallic pipe with selective surface for high absorptance in the solar wavelength region and low emittance in the thermal region. The fluid flowing inside the receiver is water. A glass cover is placed around the receiver pipe to reduce the thermal radiation losses to the environment (greenhouse effect). Also, to eliminate the conduction-convection losses, the pressure in the space between the receiver and the glass is kept below 10^{-6} atm, as illustrated in Section 3 (see Fig. 4.1).

The steady state energy balance for the receiver tube and the glass cover is given by the first law of thermodynamics.

For the receiver tube (the index 2 denotes the surface of the receiver tube):

$$q_{s,2} + q_{l,2} + q_u = 0 \quad (4.1)$$

For the glass cover (the index 1 denotes the surface of the glass cover):

$$q_{s,1} + q_{l,1} + q_{1,env} = 0 \quad (4.2)$$

where

- $q_{s,2}$ - solar radiation absorbed by the receiver tube
- $q_{l,2}$ - radiation exchange in the long wavelength region
(thermal) between the receiver and its environment
- q_u - useful energy delivered by the working fluid
- $q_{s,1}$ - solar radiation absorbed by the glass cover
- $q_{l,1}$ - radiation exchange in the long wavelength region
between the glass cover and its environment
- $q_{l,env}$ - convection losses from the glass to the environment

4.1.2 Solar Radiation Directed Toward the Receiver Pipe

The solar radiation directed towards the receiver consists of two parts:

- a) the solar radiation coming after reflection from the reflector and,
- b) the radiation coming directly from the sun.

The radiation coming after reflection from the reflector is: [5]

$$SRI_a = F_{opt} I_D \rho_r \Delta x [a - D_1 + (D_1 - D_2) \tau_1^2]$$

The radiation coming directly from the sun is:

$$SRI_b = I_D D_2 \Delta x$$

The total solar radiation is:

$$SRI = F_{opt} I_D \rho_r \Delta x [a - D_1 + (D_1 - D_2) \tau_1^2] + I_D D_2 \Delta x \quad (4.3)$$

4.1.3 Useful Energy Delivered

The energy balance for the fluid flowing through a segment Δx of the receiver tube is:

$$\dot{V} \rho C_p (T_{f \text{ out}} - T_{f \text{ in}}) = h_c \pi D_{2 \text{ in}} \Delta x (T_2 - \bar{T}_f) \quad (4.4)$$

where $\bar{T}_f$ is the bulk or mean fluid temperature.

Eqn. (4.4) can be written in differential form as:

$$\frac{dT_f}{dx} = \xi (T_2 - T_f) \quad (4.5)$$

where T_f is the fluid temperature at point x and

$$\xi = \frac{h_c \pi D_{2 \text{ in}}}{\dot{V} \rho C_p}$$

For small increments dx , T_2 is assumed constant. Then eqn. (4.5)

becomes :

$$\frac{d(T_2 - T_f)}{T_2 - T_f} = -\xi dx$$

by integrating with respect to x between x_1 and x_2 with $x_2 - x_1 = \Delta x$

and with respect to T_f between $T_{f \text{ out}}$ and $T_{f \text{ in}}$:

$$T_{f \text{ out}} = T_{f \text{ in}} \exp(-\xi \Delta x) + T_2 (1 - \exp(-\xi \Delta x)) \quad (4.6)$$

By substituting Eqn. (4.6) into Eqn. (4.4), the mean fluid temperature is obtained as:

$$\bar{T}_f = T_2 + \frac{(T_{f \text{ in}} - T_2) (1 - \exp(-\xi \Delta x))}{\xi \Delta x} \quad (4.7)$$

and the useful energy delivered

$$q_u = h_c \pi D_{2 \text{ in}} \Delta x (T_2 - \bar{T}_f) \quad (4.8)$$

The heat transfer coefficient is calculated as follows: [1,3]

For laminar flow ($Re < 2100$):

$$Nu = \frac{48.0}{11.0} + \frac{0.0668 (D_{2 \text{ in}} / \Delta x) Re Pr}{1 + 0.04 [(D_{2 \text{ in}} / \Delta x) Re Pr]^{2/3}} \quad (4.9)$$

For turbulent flow ($5000 < Re < 1.25 \times 10^5$):

$$Nu = (f/8) Re Pr / [1.07 + 12.7 \sqrt{f/8} (Pr^{2/3} - 1)] \quad (4.10)$$

where f is the friction factor given by

$$f = [1.82 \log_{10} Re - 1.64]^{-2}$$

In the transition region $2100 < Re < 5000$:

$$Nu = 0.166 (Re^{2/3} - 125) Pr^{1/3} [1 + (D_{2 \text{ in}} / \Delta x)^{2/3}] (\mu / \mu_w)^{1/7} \quad (4.11)$$

where μ and μ_w are the dynamic viscosity of the fluid calculated at the T_f and the temperature at the wall, respectively.

4.1.4 Sky Radiation

Swinbank relates the sky temperature to the local ambient temperature with the formula [6]:

$$T_{\text{sky}} = 0.0552 T_a^{1.5}$$

T_{sky} and T_a are in K.

The sky radiation is:

$$E_{\text{ob}} = \sigma T_{\text{sky}}^4 = 9.2845 \cdot 10^{-6} \sigma T_a^6 \quad (4.12)$$

where σ is the Stefan-Boltzmann constant, which has the value

$$\sigma = 5.669 \times 10^{-8} \text{ W/m}^2 \text{K}^4$$

4.1.5 Convective Losses from the Glass Cover to the Environment

For air flow across a single tube for outdoor conditions, McAdams [6] recommends:

$$\text{Nu} = 0.40 + 0.54 (\text{Re})^{0.52} \quad (4.13)$$

For $0.1 < \text{Re} = \frac{w D_1}{\nu} < 1000$ and

$$\text{Nu} = 0.30 (\text{Re})^{0.60} \quad (4.14)$$

For $1000 < \frac{w D_1}{\nu} < 50000$

Therefore, the convective heat losses for each case will be:

For $0.1 < \frac{w D_1}{\nu} < 1000$

$$q_{1,env} = \frac{\kappa_a}{D_1} [0.40 + 0.54 (Re)^{0.52}] (T_1 - T_a) \quad (4.15)$$

For $1000 < \frac{w D_1}{v} < 50000$

$$q_{1,env} = \frac{\kappa_a}{D_1} 0.30 (Re)^{0.60} (T_1 - T_a) \quad (4.16)$$

4.1.6 Radiation Exchange in the Long Wavelength Region Between the Surfaces of the Absorber and the Environment of Each

The radiation exchange is calculated by the use of the network method as introduced by A.K. Oppenheim [7].

The surface of the glass cover is assumed to have a specular and a diffuse component of reflectance and transmittance. Therefore, for the glass surface:

$$\alpha_1' + \tau_{1D} + \tau_{1S} + \rho_{1S} + \rho_{1D} = 1 \quad (4.16)$$

$$\alpha_1' = \epsilon_1' \quad (4.17)$$

For the receiver tube:

$$\alpha_2' + \rho_2' = 1 \quad (4.18)$$

$$\alpha_2' = \epsilon_2' \quad (4.19)$$

The environment is assumed to behave as a black body. The specular-transmitted radiation exchange between surfaces 0-2 (see Fig. 4.2) may be calculated directly:

$$q_{0 \rightarrow 2}^s = J_0 A_0 F_{0 \rightarrow 2} \tau_{1s}$$

$$q_{2 \rightarrow 0}^s = J_2 A_2 F_{2 \rightarrow 0} \tau_{1s}$$

where J_0, J_2 are the radiosities of the surface 0 and 2, respectively, $F_{0 \rightarrow 2}$ and $F_{2 \rightarrow 0}$ are the configuration factors from surface 0 to surface 2 ($F_{0 \rightarrow 2}$) and from surface 2 to surface 0 ($F_{2 \rightarrow 0}$).

By using the reciprocity relation, $A_0 F_{0 \rightarrow 2} = A_2 F_{2 \rightarrow 0}$ and the fact that $F_{2 \rightarrow 0} = 1$ (all the radiation leaving the surface 2 goes to the surface 0)

$$F_{0 \rightarrow 2} = \frac{A_2}{A_0}$$

The net specular transmitted radiation is

$$q_{02}^s = q_{0 \rightarrow 2}^s - q_{2 \rightarrow 0}^s = A_2 \tau_{1s} (J_0 - J_2) = \frac{J_0 - J_2}{1/A_2 \tau_{1s}}$$

but also $J_0 = E_{0b}$ because the environment is a black body

$$q_{02}^s = \frac{E_{0b} - J_2}{1/A_2 \tau_{1s}} \quad (4.20)$$

The space resistance between the radiosity potentials E_{0b} and J_2 (see Fig. 4.3 for the network diagram) is denoted by

$$R_1 = 1/A_2 \tau_{1s}$$

For the diffuse transmitted radiation, the energy leaving surface 0 and transmitted diffusely through the glass is

$$J_0 A_0 F_{0 \rightarrow 1} \tau_{1D}$$

The portion of this energy arriving at surface 2 is

$$q_{0 \rightarrow 2}^D = J_0 A_0 F_{0 \rightarrow 1} F_{1 \rightarrow 2} \tau_{1D}$$

Similarly,

$$q_{2 \rightarrow 0}^D = J_2 A_2 F_{2 \rightarrow 1} F_{1 \rightarrow 0} \tau_{1D}$$

Using the reciprocity relations

$$A_0 F_{0 \rightarrow 1} = A_1 F_{1 \rightarrow 0}, A_1 F_{1 \rightarrow 2} = A_2 F_{2 \rightarrow 1} \text{ and } F_{1 \rightarrow 0} = F_{2 \rightarrow 1} = 1$$

$q_{0 \rightarrow 2}^D$ is given by

$$q_{0 \rightarrow 2}^D = J_0 A_0 F_{0 \rightarrow 1} F_{1 \rightarrow 2} \tau_{1D} = E_{0b} A_2 F_{1 \rightarrow 0} F_{2 \rightarrow 1} \tau_{1D}$$

and the net diffuse transmitted energy is

$$q_{02}^D = \frac{E_{0b} - J_2}{1/A_2 \tau_{1D}} \quad (4.21)$$

The space resistance between surface 0 and 2 is denoted by

$$R_2 = 1/A_2 \tau_{1D}$$

The radiation exchange between surfaces 0 and 1 is calculated as follows.

The portion of energy leaving surface 0, arriving at surface 1 and contributing to the diffuse radiosity, is

$$q_{0 \rightarrow 1}^D = J_0 A_0 F_{0 \rightarrow 1} (1 - \tau_{1D} - \tau_{1S} - \rho_{1S})$$

The diffuse energy leaving surface 1 and arriving at surface 0 is

$$q_{1 \rightarrow 0}^D = J_{1D}^{\text{out}} A_1 F_{1 \rightarrow 0}$$

where J_{1D}^{out} is the diffuse radiosity of the outer side of surface 1.

1. Using the reciprocity relation $A_1 F_{1 \rightarrow 0} = A_0 F_{0 \rightarrow 1}$ and $F_{1 \rightarrow 0} = 1$, the net diffuse radiation exchange is:

$$q_{01}^D = \frac{E_{0b} - J_{1D}^{\text{out}} / (1 - \tau_{1D} - \tau_{1S} - \rho_{1S})}{1/A_1 (1 - \tau_{1D} - \tau_{1S} - \rho_{1S})} \quad (4.22)$$

The space resistance between surfaces 0 and 1 is denoted by

$$R_3 = 1/A_1 (1 - \tau_{1D} - \tau_{1S} - \rho_{1S})$$

The diffuse radiosity of surface 1 for the outer side is [8]:

$$J_{1D}^{\text{out}} = \epsilon_1 E_{1b} + \rho_{1D} G_1^{\text{out}} \quad (4.23)$$

where G_1^{out} is the irradiation of surface 1 for the outer side
and $E_{1b} = \sigma T_1^4$ is the thermal emissive power of surface 1.

The net radiation leaving the outer side of surface 1 is:

$$q_1^{\text{out net}} = A_1 (\epsilon_1' E_{1b} - \alpha_1' G_1^{\text{out}}) \quad (4.24)$$

From Eqn. (4.23),

$$G_1^{\text{out}} = \frac{J_{1D}^{\text{out}} - \epsilon_1' E_{1b}}{\rho_{1D}}$$

and Eqn. (4.24)

$$q_1^{\text{out net}} = \frac{E_{1b} - J_{1D}^{\text{out}} / (1 - \tau_{1D} - \tau_{1S} - \rho_{1S})}{\rho_{1D} / A_1 \epsilon_1' (1 - \tau_{1D} - \tau_{1S} - \rho_{1S})} \quad (4.25)$$

The surface resistance is denoted by:

$$R_4 = \rho_{1D} / A_1 \epsilon_1' (1 - \tau_{1D} - \tau_{1S} - \rho_{1S})$$

With similar analysis, the surface resistance of the inner side of surface 1 is:

$$R_5 = \rho_{1D} / A_1 \epsilon_1' (1 - \tau_{1D} - \tau_{1S} - \rho_{1S})$$

Similarly, the space resistance between surfaces 1 and 2 is:

$$R_6 = 1/A_2 (1 - \tau_{1S} - \tau_{1D} - \rho_{1S})$$

The radiosity of surface 2 is:

$$J_2 = \epsilon_2' E_{2b} + \rho_2' G_2$$

or

$$G_2 = \frac{J_2 - \epsilon_2' E_{2b}}{\rho_2'}$$

The net energy leaving surface 2 is:

$$q_2^{\text{net}} = A_2 (J_2 - G_2)$$

or

$$q_2^{\text{net}} = \frac{E_{2b} - J_2}{(1 - \epsilon_2') / \epsilon_2' A_2} \quad (4.26)$$

The surface resistance is denoted by:

$$R_7 = (1 - \epsilon_2') / \epsilon_2' A_2.$$

The radiation exchanges within the system are shown in the network diagram (Fig. 4.3).

The radiation exchange of surface 1 with its environment is:

$$q_{1,1} = \frac{B-C}{R_4} + \frac{D-C}{R_5} \quad (4.27)$$

and the radiation exchange of surface 2 with its environment is:

$$q_{2,2} = \frac{E-F}{R_7} \quad (4.28)$$

The unknowns in the above two equations are B, D, E. Using the energy balance of node B:

$$\frac{A-B}{R_3} + \frac{C-B}{R_4} = 0 \quad (4.29)$$

At node D:

$$\frac{C-D}{R_5} + \frac{E-D}{R_6} = 0 \quad (4.30)$$

At node E:

$$\frac{A-E}{R_1 R_2 / (R_1 + R_2)} + \frac{D-E}{R_6} + \frac{F-E}{R_7} = 0 \quad (4.31)$$

By solving this system: ($A=E_{0b}$, $C=E_{1b}$, $F=E_{2b}$)

$$B = \frac{E_{0b} R_4 + E_{1b} R_3}{R_3 + R_4} \quad (4.32)$$

$$E = \frac{\frac{E_{0b}}{R_1 R_2 / (R_1 + R_2)} + \frac{E_{2b}}{R_7} + \frac{E_{1b}}{(R_5 + R_6)}}{\frac{R_1 + R_2}{R_1 R_2} + \frac{1}{R_6} + \frac{1}{R_7} - \frac{R_5}{(R_6 (R_5 + R_6))}} \quad (4.33)$$

and

$$D = \frac{E_{1b} R_6 + E_{2b} R_5}{R_5 + R_6} \quad (4.34)$$

4.1.7 Radiation Exchange in the Solar Wavelength Region Between the Surfaces of the Absorber and the Sun

The radiation exchange in the solar wavelength region will also be calculated by using the network method and the following assumptions:

1. The surfaces of the glass and the receiver are specular for solar radiation.
2. The thermal emissive powers of the glass cover and the receiver tube are zero.
3. The reflector is a cylindrical surface around the absorber pipe and the total radiation leaving the reflector and directed towards the absorber pipe is SRI.
4. All the configuration factors between the surfaces of the absorber and the reflector are unity.

The radiation analysis is as follows. The energy leaving surface 0 and arriving at surface 2 is (see Fig. 4.4):

$$q_{0 \rightarrow 2} = \text{SRI } \tau_1$$

The energy leaving surface 2 and arriving at surface 0 is:

$$q_{2 \rightarrow 0} = J_2 A_2 \tau_1$$

The net radiation is:

$$q_{02} = (\text{SRI} - J_2 A_2) \tau_1$$

or

$$q_{02} = \frac{SRI - J_2 A_2}{1/\tau_1} \quad (4.35)$$

The space resistance is denoted by $R_1 = 1/\tau_1$ (see network diagram Fig. 4.5).

The radiation exchange between surfaces 0 and 1 is calculated as follows.

The radiation leaving surface 0 and arriving at surface 1 is:

$$q_{0 \rightarrow 1} = SRI(1 - \tau_1)$$

The radiation leaving surface 1 and arriving at surface 0 is:

$$q_{1 \rightarrow 0} = J_1^{\text{out}} A_1$$

The net radiation is:

$$q_{01} = SRI(1 - \tau_1) - J_1^{\text{out}} A_1$$

or

$$q_{01} = \frac{SRI - J_1^{\text{out}} A_1 (1 - \tau_1)}{1/(1 - \tau_1)} \quad (4.36)$$

The space resistance is denoted by:

$$R_2 = 1/(1 - \tau_1)$$

The outer resistance of surface 1 is calculated as follows. The outer radiosity of surface 1 is:

$$J_1^{\text{out}} = \rho_1 G_1^{\text{out}}$$

The net radiation arriving at surface 1 is:

$$q_1^{\text{out net}} = A_1 \alpha_1 G_1^{\text{out}} = A_1 \alpha_1 \frac{J_1^{\text{out}}}{\rho_1}$$

or

$$q_1^{\text{out net}} = \frac{A_1 J_1^{\text{out}} / (1 - \tau_1)}{\rho_1 / \epsilon_1 (1 - \tau_1)} \quad (4.37)$$

The space resistance of surface 1 of the outer side is denoted by:

$$R_3 = \frac{1}{\rho_1 / \epsilon_1 (1 - \tau_1)}$$

With similar analysis, the surface resistance of the inner side is:

$$R_4 = \rho_1 / \epsilon_1 (1 - \tau_1)$$

For the radiation exchange between surfaces 1 and 2, the energy leaving surface 1 and arriving at surface 2 is:

$$q_{1 \rightarrow 2} = J_1^{\text{in}} A_1$$

The energy leaving surface 2 and arriving at surface 1 is:

$$q_{2 \rightarrow 1} = J_2 A_2 (1 - \tau_1)$$

The net radiation exchange is:

$$q_{12} = q_{1 \rightarrow 2} - q_{2 \rightarrow 1} = \frac{J_1^{\text{in}} A_1 / (1 - \tau_1) - J_2 A_2}{1 / (1 - \tau_1)} \quad (4.38)$$

The space resistance between surfaces 1 and 2 is denoted by:

$$R_5 = 1 / (1 - \tau_1)$$

The radiosity of surface 2 is:

$$J_2 = \rho_2 G_2$$

The net radiation arriving at surface 2 is:

$$q_2^{\text{net}} = A_2 \alpha_2 G_2 = A_2 \epsilon_2 \frac{J_2}{\rho_2}$$

or

$$q_2^{\text{net}} = \frac{A_2 J_2}{\rho_2 / \epsilon_2}$$

The surface resistance is:

$$R_6 = \frac{\rho_2}{\epsilon_2}$$

The net solar radiation gain for each surface is, (see network diagram Fig. 4.5):

$$q_{s,1} = \frac{B+D}{R_3} \quad (4.39)$$

$$q_{s,2} = \frac{E}{R_6} \quad (4.40)$$

In order to calculate the solar energy absorbed by surfaces 1 and 2, the values of B, D, and E must be calculated.

From the node B:

$$\frac{A-B}{R_2} + \frac{-B}{R_3} = 0 \quad (4.41)$$

From the node D:

$$\frac{-D}{R_4} + \frac{E-D}{R_5} = 0 \quad (4.42)$$

From the node E:

$$\frac{A-E}{R_1} + \frac{D-E}{R_5} + \frac{-E}{R_6} = 0 \quad (4.43)$$

Solving this system yields:

$$B = \frac{SRI R_3}{R_2 + R_3} \quad (4.44)$$

$$E = (SRI/R_1) / \left(\frac{1}{R_1} + \frac{1}{R_5} + \frac{1}{R_6} - \frac{R_4}{R_5(R_4 + R_5)} \right) \quad (4.45)$$

$$D = \frac{ER_4}{R_4 + R_5} \quad (4.46)$$

4.1.8 Results

The performance of each collector is best described as a function of its thermal efficiency, which is defined as:

$$\begin{aligned} \eta_{th} &= \frac{\text{Useful energy delivered by the working fluid}}{\text{Total incident radiation}} \\ &= \frac{q_u}{I_D a \ell} \end{aligned} \quad (4.47)$$

This shows that in order to calculate the thermal efficiency, the useful energy has to be known. This is a function of

the variables listed in this section and the temperatures of the receiver tube and glass cover which are calculated by solving a system of two non-linear equations (4.1 and 4.2).

A computer program has been compiled to solve the system of equations mentioned above, following the analysis developed in Section 4.1. The program is listed in Appendix 3,4. The outputs are the temperatures of the receiver tube, glass cover and water coming out and the efficiency of the collector. A step-by-step solution is employed in which the temperature of the water coming out of one step is used as the input water temperature for the next step. The number of steps to be taken can be changed at will. The reason for this step-by-step solution is to show how the efficiency and temperature of the water out vary along the length of the collector (see Fig. 4.6).

The program is flexible in that several constants can be varied to enable examination of the performance under different sets of conditions. It is worthy of mentioning that overall results (i.e. an outlet of the collector) may be obtained by using a step size equal to the entire length of the collector.

The results are summarized in Figs. 4.7 to 4.9. The following set of properties is used throughout (see nomenclature for the symbols).

$\tau_{1S} = 0.01$	$\alpha_1 = 0.1$
$\tau_{1D} = 0.09$	$\rho_2 = 0.1$
$\rho_{1S} = 0.01$	$\alpha_2 = 0.9$
$\rho_{1D} = 0.09$	$l = 4.0m$
$\alpha'_1 = 0.80$	$D_1 = 0.05m$
$\alpha'_2 = 0.10$	$D_2 = 0.02m$
$\rho'_2 = 0.90$	$D_{2in} = 0.018m$
$\tau_1 = 0.80$	$a = 2.0m$
$\rho_1 = 0.10$	$w = 10km/hr$
	$T_a = 20^\circ C$
	$T_{f in} = 50^\circ C$

Fig. 4.6 shows the thermal efficiency as a function of the water temperature along the length of the receiver tube (lengths marked on curve) with the particular set of conditions shown on the figure. The various constants used (indicated in figures 4.6 to 4.9) are representative in solar collection practice. It can be seen that by using a very low flow rate, increasing water temperature (i.e. increasing length along the receiver tube) drops the efficiency slightly.

The variation of the overall efficiency and outlet temperature as a function of the reflectance of the reflector surface is presented in Fig. 4.7. With increasing reflectance, both the efficiency and outlet temperature are increased.

The same applies to the case where the intercept factor is varied (Fig. 4.8).

Fig. 4.9 shows the variation of the thermal efficiency and outlet temperature as a function of the incident radiation. The thermal efficiency remains practically constant (high flow rate) while the outlet temperature increases with increasing incident radiation.

4.2 Thermal Analysis of the First Configuration with Two Glass Covers

4.2.1 Energy Balance

The only difference in this configuration with the previous one is one more glass cover. The reason for this is the difficulty of sealing between the metal receiver pipe and the glass.

In this configuration, the evacuated space is between the two glasses with permanent sealing. It is also assumed that the pressure is below 10^{-6} atm and the heat losses by conduction-convection from the inner to the outer cover is thus negligible. Only a poor seal is needed between the receiver and the inner cover to keep the air in this space stagnant (see Fig. 4.10).

The steady state energy balance of the surfaces of the absorber is as follows.

For the receiver tube (the index 3 denotes the surface of the receiver tube):

$$q_{s,3} + q_{l,3} + q_{cc,(3 \rightarrow 2)} + q_u = 0 \quad (4.48)$$

For the inner glass cover (the index 2 denotes the surface of the inner glass cover):

$$q_{s,2} + q_{l,2} + q_{oc,(2+3)} = 0 \quad (4.49)$$

For the outer glass cover (the index 1 denotes the surface of the outer glass cover):

$$q_{s,1} + q_{l,1} + q_{1,env} = 0 \quad (4.50)$$

where

- $q_{s,3}$ - solar radiation absorbed by the receiver tube
- $q_{l,3}$ - radiation exchange in the long wavelength region between the receiver and its environment
- $q_{oc,(3-2)}$ - combined conduction-convection losses from the receiver tube to the inner cover
- q_u - useful energy delivered by the working fluid
- $q_{s,2}$ - solar radiation absorbed by the inner cover
- $q_{l,2}$ - radiation exchange in the long wavelength region between the inner cover and its environment
- $q_{s,1}$ - solar radiation absorbed by the outer cover
- $q_{l,1}$ - radiation exchange in the long wavelength region between the outer cover and its environment
- $q_{1,env}$ - convection losses from the outer cover to the environment

Both q_u and $q_{1,env}$ have been calculated in Sections 4.1.3 and 4.1.5, respectively.

4.2.2 Solar Radiation Directed Toward the Receiver Pipe

The radiation coming after reflection from the reflector is:

$$SRI_a = F_{opt} I_L \rho_r \Delta x [a - D_1 + (D_1 - D_2) \tau_1^2 + (D_2 - D_3) \tau_1^2 \tau_2^2]$$

The radiation coming directly from the sun is:

$$SRI_b = I_D D_3 \Delta x$$

The total radiation is:

$$\begin{aligned} SRI &= F_{opt} I_D \rho_r \Delta x [a - D_1 + (D_1 - D_2) \tau_1^2 + (D_2 - D_3) \tau_1^2 \tau_2^2] \\ &\quad + I_D D_3 \Delta x \end{aligned} \quad (4.51)$$

4.2.3 Combined Conduction-Convection Losses from the Receiver Tube to the Inner Cover

Between the receiver tube and the inner cover, there is air moved only due to free convection at atmospheric pressure. From Chapter 3,

$$q_{cc, (3+2)} = (A_3 + A_2) \frac{k_{eq}}{2\delta} (T_2 - T_3) \quad (4.52)$$

with

$$\delta = \frac{D_2 - D_3}{2}$$

and

$$\frac{k_{eq}}{k} = 0.18 (Gr Pr)^{0.25}$$

and for $250\text{K} < \frac{T_2 + T_3}{2} < 500\text{K}$.

$$\text{Gr Pr} = 2737(1+2b)^2 b^4 \Delta T (100\delta)^3$$

with

$$b = 200 / (T_2 + T_3).$$

4.2.4 Radiation Exchange in the Long Wavelength Region Between the Surfaces of the Absorber and the Environment of Each

The network method is again used to carry out the radiation analysis. A complete analysis is presented in Appendix 2A and a summary of the results is given below. This is done so that the flow of thoughts of the reader is not disturbed by an extremely lengthy analysis. The interested reader might afterward refer to the Appendix to follow the complete analysis.

A description of the symbols used in the network diagram that follows can be found in Appendix 2A.

The net radiation exchanges within the system are (see Fig. 4.11):

For the cover 1:

$$q_{l,1} = \frac{B-C}{R_4} + \frac{D-C}{R_4} \quad (4.53)$$

For cover 2:

$$q_{l,2} = \frac{E-F}{R_6} + \frac{G-F}{R_6} \quad (4.54)$$

For the receiver tube:

$$q_{l,3} = \frac{H-I}{R_{12}} \quad (4.55)$$

4.2.5 Radiation Exchange in the Solar Wavelength Region Between the Surfaces of the Absorber and the Sun

A complete analysis of the radiation exchange is carried out in Appendix 2B and a summary of the results is presented below.

The net solar gain of each surface is (see network diagram Fig. 4.12).

For cover 1:

$$q_{s,1} = \frac{B+D}{R_3} \quad (4.56)$$

For cover 2:

$$q_{s,2} = \frac{E+G}{R_5} \quad (4.57)$$

For the receiver tube:

$$q_{s,3} = \frac{H}{R_9} \quad (4.58)$$

4.2.6 Results

A computer program has been compiled to analyze this configuration (see Appendix 5). The graphical analysis is along the same lines with Section 4.1.8. The following set of conditions is used in this case (see nomenclature for symbols).

τ_{1S}	= 0.01	ρ_2	= 0.1
τ_{2S}	= 0.01	α_1	= 0.1
τ_{1D}	= 0.09	α_2	= 0.1
τ_{2D}	= 0.09	ρ_3	= 0.1
ρ_{1S}	= 0.01	α_3	= 0.9
ρ_{2S}	= 0.01	l	= 4.0
ρ_{1D}	= 0.09	D_1	= 0.08m
ρ_{2D}	= 0.09	D_2	= 0.05m
α'_1	= 0.8	D_3	= 0.02m
α'_2	= 0.8	D_{3in}	= 0.018m
α'_3	= 0.1	T_{fin}	= 50°C
ρ'_3	= 0.9	a	= 2.0m
τ_1	= 0.8	w	= 10km/hr
τ_2	= 0.8	T_a	= 20 °C
ρ_1	= 0.1		

Curves corresponding to each of the curves of Section 4.1.8 have been plotted (see Figs. 4.13 to 4.16) and compared in the following section.

4.2.7 Comparison of Results - Vacuum Loss Effect

Comparison of the efficiencies of the configurations is best achieved after analysis of vacuum effects in the single-glass absorber due to poor sealing between the glass envelope and the receiver pipe. A new term which takes care of the conduction-

convection losses (appreciable at pressures above 10^{-6} atm) has been added to the system of Eqns. (4.1) and (4.2). The form of the new system is:

For the receiver tube:

$$q_{s,2} + q_{l,2} + q_u - q_{cc} = 0 \quad (4.1a)$$

For the glass cover:

$$q_{s,1} + q_{l,1} + q_{l,env} + q_{cc} = 0 \quad (4.2a)$$

where q_{cc} is the conduction-convection loss term and is calculated as analyzed in Section 3.

A computer program has been compiled to solve Eqns. (4.1a) and (4.2a) (Appendix 6). This program determines the efficiency as a function of the pressure and the results are summarized in Figs. 4.17 and 4.18.

It can be observed that at high flow rates (fluid temperatures below 100°C), the efficiency of the single-glass absorber is better than the double-glass absorber, even at a complete loss of vacuum. In the case of low flow rates (high fluid temperatures), the effects of loss of vacuum are appreciable, resulting in efficiencies of the single-glass absorber dropping by about 40% figure 4.17 (complete loss of vacuum results in a 34% efficiency). Therefore, in this case (high temperatures), the double-glass absorber is preferable to the single-glass absorber. (figure 4.13)

Figure 4.1 Schematic diagram of the absorber pipe
(first configuration with one glass cover).

Surface

- 0 - Environment
- 1 - Glass cover
- 2 - Receiver tube

Figure 4.2 Cross-section of the absorber pipe and the surface of
the environment (first configuration with one glass
cover).

where

- A = E_{0b} - Surface of the environment
- B = $J_{1D}^{out} / (1 - \tau_{1s} - \tau_{1D} - \rho_{1s})$ - Outer side of the glass cover
- C = E_{1b} - glass cover
- D = $J_{1D}^{in} / (1 - \tau_{1s} - \tau_{1D} - \rho_{1s})$ - Inner side of the glass cover
- E = J_2 - Outer side of the receiver pipe
- F = E_{2b} - Receiver pipe.

$$\begin{aligned}
 R_1 &= 1/A_2 \tau_{1s} & R_5 &= \rho_{1D}/A_1 \epsilon_1' (1 - \tau_{1s} - \tau_{1D} - \rho_{1s}) \\
 R_2 &= 1/A_2 \tau_{1D} & R_6 &= 1/A_2 (1 - \tau_{1s} - \tau_{1D} - \rho_{1s}) \\
 R_3 &= 1/A_1 (1 - \tau_{1s} - \tau_{1D} - \rho_{1s}) & R_7 &= (1 - \epsilon_2)/A_2 \epsilon_2 \\
 R_4 &= \rho_{1D}/A_1 \epsilon_1' (1 - \tau_{1s} - \tau_{1D} - \rho_{1s}) & R_{eq} &= R_1 R_2 / (R_1 + R_2)
 \end{aligned}$$

Figure 4.3 Network diagram showing radiation exchanges in the long wavelength region (first configuration with one glass cover).

Surface

- 0 - Reflector
- 1 - Glass cover
- 2 - Receiver tube

Figure 4.4 Cross-section of the absorber pipe and the reflector surface (first configuration with one glass cover).

Where A = SRI - Reflector surface
 B = $J_2^{\text{out}} A_1 / (1 - \tau_1)$ - Outer side of the glass cover
 C = 0 - Glass cover
 D = $J_1^{\text{in}} A_1 / (1 - \tau_1)$ - Inner side of the glass cover
 E = $A_2 J_2$ - Outer side of the receiver pipe
 F = 0 - Receiver pipe

$$\begin{aligned} R_1 &= 1/\tau_1 \\ R_2 &= 1/(1-\tau_1) \\ R_3 &= \rho_1/\epsilon_1(1-\tau_1) \\ R_4 &= \rho_1/\epsilon_1(1-\tau_1) \\ R_5 &= 1/(1-\tau_1) \\ R_6 &= \rho_2/\epsilon_2 \end{aligned}$$

Figure 4.5 Network diagram showing radiation exchanges in the solar wave length region (first configuration with one glass cover) .

Fig. 4.6 The thermal efficiency of the collector of the first configuration with one glass cover.

Fig. 4.7 Effect of the reflector reflectance on the thermal efficiency and on the fluid temperature coming out of the absorber (First configuration with one glass cover).

Fig. 4.8 Effect of the optical intercept factor on the thermal efficiency and on the fluid temperature coming out of the absorber (First configuration with one glass cover).

Fig. 4.9 Effect of the thermal insolation on the thermal efficiency and on the temperature coming out of the absorber (First configuration with one glass cover).

Figure 4.10 Schematic diagram of the absorber pipe
(first configuration with two glass covers)

Where $A = J_0 = E_{0b}$ - Surface of the environment
 $B = J_{1D}^{out} / (1 - \tau_{1s} - \tau_{1D} - \rho_{1s})$ - Outer side of outer cover
 $C = E_{1b}$ - Outer cover
 $D = J_{1D}^{in} / (1 - \tau_{1s} - \tau_{1D} - \rho_{1s})$ - Inner side of outer cover
 $E = J_{2D}^{out} / (1 - \tau_{2s} - \tau_{2D} - \rho_{2s})$ - Outer side of Inner cover
 $F = E_{2b}$ - Inner cover
 $G = J_{2D}^{in} / (1 - \tau_{2s} - \tau_{2D} - \rho_{2s})$ - Inner side of inner cover
 $H = J_3$ - Outer side of receiver pipe
 $I = E_{3b}$

$$R_1 = 1/A_3 \tau_{1s} \tau_{2s}$$

$$R_2 = 1/A_3 \tau_{1D} \tau_{2D}$$

$$R_3 = 1/A_1 (1 - \tau_{1s} - \tau_{1D} - \rho_{1s})$$

$$R_4 = \rho_{1D}/A_1 \epsilon_1 (1 - \tau_{1s} - \tau_{1D} - \rho_{1s})$$

$$R_5 = 1/A_2 (1 - \tau_{1s} - \tau_{1D} - \rho_{1s}) (1 - \tau_{2s} - \tau_{2D} - \rho_{2s})$$

$$R_6 = \rho_{2D}/A_2 \epsilon_2 (1 - \tau_{2s} - \tau_{2D} - \rho_{2s})$$

$$R_{1eq} = R_8 R_9 / (R_8 + R_9)$$

$$R_{2eq} = R_{10} R_{11} / (R_{10} + R_{11})$$

$$R_7 = 1/A_3 (1 - \tau_{2s} - \tau_{2D} - \rho_{2s})$$

$$R_8 = 1/A_2 \tau_{1s} (1 - \tau_{2s} - \tau_{2D} - \rho_{2s})$$

$$R_9 = 1/A_2 \tau_{1D} (1 - \tau_{2s} - \tau_{2D} - \rho_{2s})$$

$$R_{10} = 1/A_3 \tau_{2D} (1 - \tau_{1s} - \tau_{1D} - \rho_{1s})$$

$$R_{11} = 1/A_3 \tau_{2s} (1 - \tau_{1s} - \tau_{1D} - \rho_{1s})$$

$$R_{12} = (1 - \epsilon_3) / A_3 \epsilon_3$$

$$R_{3eq} = R_1 R_2 / (R_1 + R_2)$$

Figure 4.11 Network diagram showing radiation exchanges in the long wave length region (first configuration with two glass covers)

Where

- A = SRI - Reflector surface
- B = $J_1^{\text{out}} A_1 / (1 - \tau_1)$ - Outer side of outer cover
- C = Q_a - Outer cover
- D = $J_1^{\text{in}} A_1 / (1 - \tau_1)$ - Inner side of outer cover
- E = $J_2^{\text{out}} A_2 / (1 - \tau_2)$ - Outer side of inner cover
- F = 0 - Inner cover
- G = $J_2^{\text{in}} A_2 / (1 - \tau_2)$ - Inner side of inner cover
- H = $J_3 H_3$ - Outer side of receiver pipe
- I = 0 - Receiver pipe

$$\begin{aligned}
 R_1 &= 1/\tau_1 + 1/\tau_2 \\
 R_2 &= 1/(1 - \tau_1) \\
 R_3 &= \rho_1 / \epsilon_1 (1 - \tau_1) \\
 R_4 &= 1/(1 - \tau_1)(1 - \tau_2) \\
 R_5 &= \rho_2 / \epsilon_2 (1 - \tau_2) \\
 R_6 &= 1/(1 - \tau_2) \\
 R_7 &= 1/\tau_1 (1 - \tau_2) \\
 R_8 &= 1/\tau_2 (1 - \tau_1) \\
 R_9 &= \rho_2 / \epsilon_2
 \end{aligned}$$

Figure 4.12 Network diagram showing radiation exchange in the solar wave length region (first configuration with two glass covers).

Fig. 4.13 The thermal efficiency of the collector of the first configuration with two glass covers.

Fig. 4.14 Effect of the reflector reflectance on the thermal efficiency and on the fluid temperature coming out of the absorber (First configuration with two glass covers).

Fig. 4.15 Effect of the optical intercept factor on the thermal efficiency and on the fluid temperature coming out of the absorber (First configuration with two glass covers).

Fig. 4.16 Effect of the thermal insolation on the thermal efficiency and on the temperature coming out of the absorber (First configuration with two glass covers).

Fig. 4.17 Effect of the pressure of the evacuated space on the thermal efficiency for low flow rate (First configuration with one glass cover)

Fig. 4.18 Effect of the pressure of the evacuated space on the thermal efficiency for high flow rate (First configuration with one glass cover) .

CHAPTER 5

THERMAL ANALYSIS OF THE SECOND CONFIGURATION

5.1 Thermal Analysis of the Second Configuration with One Glass Cover5.1.1 Energy Balance

In this configuration, the absorber consists of one glass cover and the fluid that flows inside is a black liquid with high absorptance in solar radiation (see Fig. 5.1). This black liquid is water with one or two percent indian ink. The overall absorptance of the black liquid to the solar radiation is 0.98 for a 2% and 0.95 for a 1% concentration [9,10]. In the long wavelength region, the emittance is 0.97 and the absorptance 0.03.

The steady state energy balance at the surface of the glass is (the index 1 denotes the surface of the glass cover):

$$q_{s,1} + q_{l,1} + q_{1,env} + q_u = 0 \quad (5.1)$$

The term $q_{1,env}$ has been calculated in Section 4.1.5.

5.1.2 Solar Radiation Directed Toward the Black Liquid

The radiation coming after reflection from the reflector is:

$$SRI_a = I_D F_{opt} \Delta x \rho_r (a - D_{lin})$$

The radiation coming directly from the sun is:

$$SRI_b = I_D D_{lin} \Delta x$$

The total radiation is:

$$SRI = I_D F_{opt} \Delta x \rho_r (a - D_{lin}) + I_D D_{lin} \Delta x \quad (5.2)$$

5.1.3 Useful Energy Delivered

The energy balance for a segment Δx of the fluid is:

$$\dot{V} \rho C_p (T_{f out} - T_{f in}) = h_c D_{lin} \Delta x (T_1 - \bar{T}_f) + q_{l,2} + q_{s,2} \quad (5.3)$$

where $\bar{T}_f$ is the mean fluid temperature. It is assumed that

$$\bar{T}_f = 0.5 (T_{f in} + T_{f out})$$

From Eqn. (5.3),

$$T_{f out} = \frac{0.5 h_c \pi D_{lin} \Delta x (2T_1 - T_{f in}) + q_{l,2} + q_{s,2} + \dot{V} \rho C_p T_{f in}}{\dot{V} \rho C_p + 0.5 h_c \pi D_{lin} \Delta x} \quad (5.4)$$

The heat transfer coefficient is calculated in the same way as in Section 4.1.3. The terms $q_{l,2}$ and $q_{s,2}$ are calculated in the following sections. Therefore, the useful energy is:

$$q_u = \dot{V} \rho C_p (T_{f out} - T_{f in}) \quad (5.5)$$

5.1.4 Radiation Exchange in the Long Wavelength Region Between the Surfaces of the Absorber and the Environment of Each

The radiation analysis and the results for $q_{l,1}$ and $q_{l,2}$ are exactly the same as in Section 4.1.6, by correlating the surface of the receiver tube to the surface of the black liquid.

5.1.5 Radiation Exchange in the Solar Wavelength Region Between the Surfaces of the Absorber and the Sun

The radiation analysis and the results for $q_{s,1}$ and $q_{s,2}$ are exactly the same as in Section 4.1.7, by correlating the surface of the receiver pipe to the outer surface of the black liquid.

5.1.6 Results

A computer program has been compiled (see Appendix 7) to solve the energy balance equation (5.1). This yields the temperature of the glass cover by using the following set of properties (see nomenclature for symbols).

$\tau_{1s} = 0.01$	$\alpha_1 = 0.1$
$\tau_{1D} = 0.09$	$\rho_2 = 0.02$
$\rho_{1s} = 0.01$	$\alpha_2 = 0.98$
$\rho_{1D} = 0.09$	$l = 4.0m$
$\alpha'_1 = 0.8$	$D_1 = 0.02m$
$\alpha'_2 = 0.97$	$D_{lin} = 0.018m$
$\rho'_1 = 0.03$	$T_{f \text{ in}} = 50^\circ C$
$\tau_1 = 0.8$	$a = 2.0m$
$\rho_1 = 0.1$	

The results are summarized in Figs. 5.2 to 5.8. It is worth mentioning that the cost of the absorber is comparatively low since it does not consist of a metal tube. It can also be noted that at low working fluid temperatures, the thermal efficiency

is very good (70%) but at high temperatures (above 250°C), it drops rapidly. At these high temperatures, the efficiency is very sensitive to ambient conditions (ambient temperature and wind velocity) as can be observed from Figs. 5.2 to 5.5.

The reason for the rapid degradation is efficiency under normal ambient conditions and the efficiency sensitivity under ambient conditions other than normal is the fact that there is no vacuum space. This has made obvious the necessity of using a double glass cover with an evacuated space between them, which is analyzed in the next section.

5.2 Thermal Analysis of the Second Configuration with Two Glass Covers

5.2.1 Energy Balance

In this configuration, the absorber pipe consists of two glass covers and the space between them is kept at a pressure below 10^{-6} atm to eliminate the conduction-convection losses. The black liquid water flows inside the inner glass tube (see Fig. 5.9).

The steady state energy balance for the inner and outer glass covers is as follows:

For the innerglass (the index 2 denotes the surface of the inner glass):

$$q_{s,2} + q_{l,2} + q_u = 0 \quad (5.6)$$

For the outerglass (the index 1 denotes the surface of the outer glass cover):

$$q_{s,1} + q_{l,1} + q_{1,env} = 0 \quad (5.7)$$

The term $q_{1,env}$ has been calculated in Section 4.1.5.

5.2.2 Solar Radiation Directed Toward the Black Liquid

The beam radiation coming after reflection from the reflector is:

$$SRI_a = I_D F_{opt} \Delta x \rho_r [a - D_1 + (D_1 - D_2) \tau_1^2]$$

The radiation coming directly from the sun is:

$$SRI_b = I_D D_{2in} \Delta x$$

The total radiation is:

$$SRI = I_D F_{opt} \Delta x \rho_r [a - D_1 + (D_1 - D_2) \tau_1^2] + I_D D_{2in} \Delta x \quad (5.8)$$

5.2.3 Useful Energy Delivered

The energy balance for a segment Δx of the fluid gives:

$$T_{f out} = \frac{0.5 h_c \pi D_{2in} \Delta x (2T_2 - T_{f in}) + \dot{V} \rho C_p T_{f in} + q_{l,3} + q_{s,3}}{\dot{V} \rho C_p + 0.5 h_c \pi D_{2in} \Delta x} \quad (5.9)$$

The heat transfer coefficient h_c is calculated as in Section 4.1.3. The useful energy delivered is:

$$q_u = \dot{V} \rho C_p (T_{f out} - T_{f in}) \quad (5.10)$$

5.2.4 Radiation Exchange in the Long Wavelength Region Between the Surfaces of the Absorber and the Environment of Each

The radiation analysis and the results for $q_{l,1}$, $q_{l,2}$ and $q_{l,3}$ are exactly the same as in Appendix 2A by assuming that the surface of the receiver pipe corresponds to the outer surface of the black liquid.

5.2.5 Radiation Exchange in the Solar Wavelength Region Between the Surfaces of the Absorber and the Sun

The radiation analysis and the results for $q_{s,1}$, $q_{s,2}$ and $q_{s,3}$ are exactly the same as in Appendix 2B.

5.2.6 Results

A computer program has been compiled to analyze this configuration (see Appendix 8). In this case, optical properties of the materials and geometrical characteristics of the collector are assumed to be the same as in the previous case, with an additional parameter being the diameter of the outside glass cover ($D_1 = 0.05\text{m}$).

The results are summarized in Figs. 5.10 to 5.13. It can be noted that at low temperatures ($< 200^\circ\text{C}$) the efficiency is identical to the case of the metal receiver with one glass cover, while at higher temperatures, the efficiency of the black liquid case tends to be somewhat lower. As expected, the efficiency of this configuration is improved at high temperatures as compared to the configuration of the black liquid flowing in a glass tube without an evacuated space at the expense of lower efficiencies at low temperatures.

Figure 5.1 Schematic diagram of the absorber pipe
(Second configuration with one glass cover)

Fig. 5-2 The thermal efficiency of the collector of the second configuration with one glass cover. ($T_a = 20 \text{ C}$, $w = 10 \text{ Km/hr}$)

Fig. 5-3 The thermal efficiency of the collector of the second configuration with one glass cover ($T_a = -20^\circ\text{C}$, $w = 10 \text{ km/hr}$)

Fig. 5-4 The thermal efficiency of the collector of the second configuration with one glass cover ($T_a = 20$ C, $w = 25$ Km/hr)

Fig. 5.5 The thermal efficiency of the collector of the second configuration with one glass cover. ($T_a = -20 \text{ C}$, $w = 25 \text{ Km/hr}$)

Fig. 5.6 Effect of the reflector reflectance on the thermal efficiency and on the fluid temperature coming out of the absorber (Second configuration with one glass cover).

Fig. 5.7 Effect of the optical intercept factor on the thermal efficiency and on the fluid temperature coming out of the absorber. (Second configuration with one glass cover).

Fig. 5.8 Effect of the thermal insolation on the thermal efficiency and on the temperature coming out of the absorber (Second configuration with one glass cover-).

Figure 5.9 Schematic diagram of the absorber pipe
(Second configuration with two glass covers)

Fig. 5-10 The thermal efficiency of the collector of the second configuration with two glass covers.

Fig. 5.11 Effect of the reflector reflectance on the thermal efficiency and on the fluid temperature coming out of the absorber (Second configuration with two glass covers).

Fig. 5.12 Effect of the optical intercept factor on the thermal efficiency and on the fluid temperature coming out of the absorber (Second configuration with two glass covers).

Fig. 5.13 Effect of the solar insolation on the thermal efficiency and on the temperature coming out of the absorber (Second configuration with two glass covers).

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CHAPTER 6

THERMAL ANALYSIS OF THE THIRD CONFIGURATION6.1 Energy Balance

In this configuration, the absorber pipe consists of two glass covers and inside the inner one there are small metallic spheres in the form of a packed bed. The surface of the spheres is selective with high absorptance in the solar radiation and low emittance in the thermal radiation. The space between the two glass covers is evacuated to a pressure below 10^{-6} atm to eliminate the conduction-convection losses from the inner to the outer cover. The conduit fluid in this case is air (see Fig. 6.1).

The steady state energy balance of the spherical particles which are assumed as the receiver is (the index 3 denotes the surface of the receiver):

$$q_{s,3} + q_{\ell,3} + q_{c,3} = 0 \quad (6.1)$$

For the inner cover (the index 2 denotes the surfaces of the inner cover):

$$q_{s,2} + q_{\ell,2} + q_{c,2} = 0 \quad (6.2)$$

For the outer cover (the index 1 denotes the surface of the outer cover):

$$q_{s,1} + q_{\ell,1} + q_{1,env} = 0 \quad (6.3)$$

where

$q_{c,3}$ - the heat transfer by convection from the particles to the surrounding air

$q_{c,2}$ - the heat flux from the inner cover to the flowing air.

The terms $q_{s,1}$, $q_{s,2}$, $q_{s,3}$, $q_{l,1}$, $q_{l,2}$ and $q_{l,3}$ are the same with those given in Appendix 2 by assuming that the surface area of the receiver (spherical particles) is equal to the surface area of the inner glass cover. The term $q_{1,env}$ has been calculated in Section 4.1.5.

6.2. Solar Radiation Directed Toward the Receiver Pipe

The radiation coming after reflection from the reflector is:

$$SRI_a = F_{opt} I_D \rho_r \Delta x [a - D_1 + (D_1 - D_2) \tau_1^2]$$

The radiation coming directly from the sun is:

$$SRI_b = I_D \Delta x D_2$$

The total radiation is:

$$SRI = F_{opt} I_D \rho_r \Delta x [a - D_1 + (D_1 - D_2) \tau_1^2] + I_D \Delta x D_2 \quad (6.4)$$

6.3 Heat Transfer from the Particles to the Fluid

The heat transfer coefficient from the surface of the particles to the surrounding air is very difficult to calculate because all formulae found in the literature are for specified

conditions which are not met in the case of study. For example, for d_p between 0.3m and 1mm and $Re_p > 100$ reference [11] gives:

$$Nu_p = 2 + 1.8 Pr^{1/3} Re_p^{1/2} \quad (6.5)$$

In the case of study, d_p is greater than 1cm in an effort to obtain a small pressure drop. Hence, the above formula does not apply because it would indicate a greater pressure drop.

As a consequence of the above difficulties, it was found preferable to use the formula of a single sphere in flowing air with velocity u_o [11]:

$$Nu_p = \frac{h_p d_p}{k_g} = 2 + 0.6 Pr^{1/3} \left[\frac{u_o d_p}{v_g} \right]^{1/2} \quad (6.6)$$

where k_g , Pr and v_g are the thermal conductivity, the Prandtl number and the kinematic viscosity of the fluid, respectively.

The heat transfer is:

$$q_{c,3} = h_p F (\bar{T}_f - T_3) \quad (6.7)$$

$\bar{T}_f = \frac{T_{f \text{ in}} + T_{f \text{ out}}}{2}$ is the mean fluid temperature and F is the heating surface area of the particles and is given by the following formula for a pipe length equal to Δx :

$$F = \frac{3}{d_p} (1-\epsilon) \frac{\pi D_{2in}^2}{2} \Delta x \quad (6.8)$$

ϵ is the voidage and for a bed with fine spheres is given as [12]:

$$\epsilon = 0.423 \frac{d_p}{D_{2in}} + 0.328 \quad (6.9)$$

The particles referred to above Eqn. (6.9), ranged from about 0.25 to 1.85cm. Tube diameters (D_{2in}) from about 1.50 to 10cm.

6.4 Heat Transfer from the Fluid to the Pipe

For the heat transfer coefficient from the air to the pipe in a packed bed, Leva recommends [12]:

$$17 \leq h \leq 28 \quad (w/m^2k) \quad (6.10)$$

The heat transfer is:

$$q_{C,2} = \pi D_{2in} \Delta x h (\bar{T}_f - T_2) \quad (6.11)$$

6.5 Useful Energy Delivered

The energy balance for a segment Δx of the fluid gives:

$$\begin{aligned} 0.25 u_o \pi D_{2in}^2 C_p \rho (T_{f out} - T_{f in}) \\ = h_p F (T_3 - \frac{T_{f in} + T_{f out}}{2}) + \pi D_{2in} \Delta x h (T_2 - \frac{T_{f in} + T_{f out}}{2}) \end{aligned}$$

and

$$T_{f out} = \frac{0.25 u_o \pi D_{2in}^2 C_p \rho T_{f in} + 0.5 h_p F (2T_3 - T_{f in}) + 0.5 \pi D_{2in} \Delta x h (2T_2 - T_{f in})}{0.25 u_o \pi D_{2in}^2 C_p \rho + h_p F + \pi D_{2in} \Delta x h} \quad (6.12)$$

The useful energy delivered is:

$$q_u = 0.25 u_o \pi D_{2in}^2 C_p \rho (T_{f out} - T_{f in}) \quad (6.13)$$

6.6 Pressure Drop Across the Bed

For the pressure drop, Ergun [13] suggests the following dimensionless correlation:

$$\left(\frac{\Delta P}{\rho} \right) \left(\frac{d_p}{\Delta x} \right) \left(\frac{\epsilon}{1-\epsilon} \right)^3 = 150 \frac{(1-\epsilon) \mu}{d_p G_o} + 1.75 \quad (6.14)$$

where G_o is the mass flow rate per unit cross-sectional area of empty bed. This equation is valid for $d_p G_o / \mu (1-\epsilon)$ from 1 to 2500 and ϵ from 0.40 to 0.65.

6.7 Results

Appendix 9 shows a listing of the program used to analyze this configuration. The parameters used are listed below (see nomenclature for symbols).

$\tau_{1S} = 0.01$	$\rho_1 = 0.1$	$F_{opt} = 1$
$\tau_{2S} = 0.01$	$\alpha_1 = 0.1$	$P_{in} = 2 \text{ atm}$
$\tau_{1D} = 0.09$	$\alpha_2 = 0.1$	
$\tau_{2D} = 0.09$	$\rho_3 = 0.1$	
$\rho_{1S} = 0.01$	$\alpha_3 = 0.9$	
$\rho_{2S} = 0.01$	$\ell = 4.0m$	
$\rho_{1D} = 0.09$	$D_1 = 0.1m$	
$\rho_{2D} = 0.09$	$D_2 = 0.06m$	
$\alpha'_1 = 0.8$	$D_{2in} = 0.054m$	
$\alpha'_2 = 0.8$	$T_{f \text{ in}} = 50^\circ C$	
$\alpha'_3 = 0.1$	$\rho_r = 0.90$	
$\rho'_3 = 0.9$	$T_a = 20^\circ C$	
$\tau_1 = 0.8$	$a = 2.0m$	
$\tau_2 = 0.8$	$w = 10km/hr$	

The results are summarized in Figs. 6.2 to 6.3. It can be observed that the performance is very optimistic. A possible source of error (which tends to over-estimate the efficiency) is the assumption that the surface area of the receiver (spherical particles) is equal to the surface area of the inner glass cover. Also the assumption of uniform particles temperature tends to over-estimate the thermal efficiency.

The analysis carried out in this chapter should be taken as a first order approximation of a more detailed work that may follow. This more detailed work could be undertaken as a separate project by another researcher. A more complicated model for the radiation exchange, for the heat transfer between the particles and the surrounding air, and also from the air to the glass wall could be used.

A problem inherent with a configuration with the particle size is less than one-third the tube diameter is a large pressure drop making it quite costly.

Figure 6.1 Schematic diagram of the absorber pipe
(Third configuration)

Fig. 6.2 The thermal efficiency of the collector and the pressure drop of the third configuration.. ($d_p=0.01 \text{ m}$)

Fig. 6.3 The thermal efficiency of the collector and the pressure drop of the third configuration. ($d_p = 0.015 \text{ m}$)

CHAPTER 7

DISCUSSION

In this section, a comparison of the performance of the different types of absorbers will be attempted. It will be divided into three subsections: one will be a comparison between liquid collector systems, the second will discuss the performance of the air collector and the third will consist of general conclusions and recommendations.

The choice of which liquid absorber to use for a certain application will depend on the fluid temperature required. Thus, the absorber with the highest efficiency at the operating temperature required should be chosen, provided the costs (capital and operating) of all absorbers are comparable. Of the cases considered in this report, the black liquid collector system efficiency at temperatures below 200°C is comparable to the efficiency of the collector with metallic receiver pipe and one glass cover (with perfect vacuum) and much better than the efficiency of the collector with metallic receiver pipe and two glass covers (see Fig. 7.1). It is worth noting that the black liquid collector is much less costly because there is no need for the metallic receiver pipe with selective surface which is very expensive.

In high temperature applications (above 200°C) and provided the vacuum between the receiver pipe and the glass cover remains

below 10^{-6} atmospheres, the absorber with metallic receiver and one glass cover is more efficient than all other configurations. In the case that the vacuum is below the forementioned value, both absorbers with two glass covers (metallic receiver or black liquid) are more efficient (see Fig. 7.2). The efficiencies of the last two absorbers are comparable at high temperatures, hence it may be deduced that the absorber using the black liquid should be preferred since it is less costly.

In applications where hot air is needed, there are two alternatives to be considered. One is direct heating of the air using the configuration described in Chapter 6 and the second is use of a heat exchanger in a liquid collector system. The latter is more costly since a heat exchanger arrangement has to be added. Also, the heat losses brought about in the heat exchange process will result in a lower efficiency of the system using the heat exchanger and the liquid collector.

The performance of the black liquid collector is very promising and further research should be carried out for different types of liquids. Very few works on black liquid collectors are found in the literature.

The air collector, as has been mentioned above, can be efficiently used in applications where hot air is needed. Further research on this type of receiver should be carried out with porous materials instead of metal spheres as the receiver. An experimental

Figure 7-1 Comparison of the liquid absorbers for low flow rate.

Figure 7-1 Comparison of the liquid absorbers for low flow rate.

Figure 7-2 Comparison of the liquid absorbers for high flow rate.

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APPENDIX 1

COMPUTER PROGRAM TO CALCULATE THE
OPTICAL INTERCEPT FACTOR (F_{opt})

The following program is used to calculate the optical intercept factor. The input variables used are:

D1 - diameter of the receiver pipe

APER - aperture of the reflector

SY1 - variance of ψ_1

SY2 - variance of ψ_2

The program prints the optical intercept factor as the only output.

[illegible]

APPENDIX 2

A. RADIATION EXCHANGE IN THE LONG WAVELENGTH REGION BETWEEN THE SURFACES OF THE ABSORBER AND THE ENVIRONMENT OF EACH - FIRST CONFIGURATION WITH TWO GLASS COVERS

The radiation analysis is based on the network method. It is assumed that the surfaces of the transmitting media (the two covers) have a specular and a diffuse component of reflectance and transmittance [8].

For the outer cover (see Fig. 2A-1):

$$\alpha_1' + \tau_{1D} + \tau_{1S} + \rho_{1S} + \rho_{1D} = 1 \quad (2A1)$$

$$\alpha_1' = \epsilon_1' \quad (2A2)$$

For the inner cover:

$$\alpha_2' + \tau_{2S} + \tau_{2D} + \rho_{2S} + \rho_{2D} = 1 \quad (2A3)$$

$$\alpha_2' = \epsilon_2' \quad (2A4)$$

For the receiver tube:

$$\alpha_3' + \rho_3' = 1 \quad (2A5)$$

$$\alpha_3' = \epsilon_3' \quad (2A6)$$

The environment is assumed to behave as a black body.

The specular-transmitted radiation exchange between surfaces 0-3 may be calculated directly as:

$$q_{0 \rightarrow 3}^S = J_0 A_0 F_{0 \rightarrow 3} \tau_{1S} \tau_{2S}$$

and

$$q_{3 \rightarrow 0}^S = J_3 A_3 F_{3 \rightarrow 0} \tau_{1S} \tau_{2S}$$

The configuration factor $F_{3 \rightarrow 0}$ is unity because all the radiation leaving surface 3 arrives at surface 0. By using the reciprocity relation

$$A_0 F_{0 \rightarrow 3} = A_3 F_{3 \rightarrow 0}$$

and

$$F_{3 \rightarrow 0} = 1.$$

The configuration factor $F_{0 \rightarrow 3}$ is A_3/A_0 .

The net specular transmitted radiation is:

$$q_{03}^S = A_3 \tau_{1S} \tau_{2S} (J_0 - J_3)$$

The radiosity J_0 is the thermal emissive power of the environment E_{0b} , therefore

$$q_{03}^S = \frac{E_{0b} - J_3}{1/A_3 \tau_{1S} \tau_{2S}} \quad (2A7)$$

The surface resistance is denoted by: (see Fig. 2A-2)

$$R_1 = 1/A_3 \tau_{1S} \tau_{2S}$$

The diffuse transmitted radiation exchange is a little more complicated. The energy leaving surface 0 and transmitted

diffusely through cover 1 is:

$$E_{0b} A_0 F_{0 \rightarrow 1} \tau_{1D}$$

The portion of this energy arriving at surface 2 is:

$$E_{0b} A_0 F_{0 \rightarrow 1} \tau_{1D} F_{1 \rightarrow 2}$$

The portion of energy transmitted through surface 2 and finally arriving at surface 3 is:

$$q_{0 \rightarrow 3}^D = E_{0b} A_0 F_{0 \rightarrow 1} F_{1 \rightarrow 2} F_{2 \rightarrow 3} \tau_{1D} \tau_{2D}$$

Similarly

$$q_{3 \rightarrow 0}^R = J_3 A_3 F_{3 \rightarrow 2} F_{2 \rightarrow 1} F_{1 \rightarrow 0} \tau_{1D} \tau_{2D}$$

From the reciprocity relation,

$$A_0 F_{0 \rightarrow 1} = A_1 F_{1 \rightarrow 0}$$

$$A_1 F_{1 \rightarrow 2} = A_2 F_{2 \rightarrow 1}$$

$$A_2 F_{2 \rightarrow 3} = A_3 F_{3 \rightarrow 2}$$

$$F_{1 \rightarrow 0} = F_{2 \rightarrow 1} = F_{3 \rightarrow 2} = 1$$

It can be shown that the net diffuse transmitted radiation is:

$$q_{03}^D = \frac{E_{0b} - J_3}{1/A_3 \tau_{1D} \tau_{2D}} \quad (2A8)$$

The space resistance is denoted by:

$$R_2 = 1/A_3 \tau_{1D} \tau_{2D}$$

The radiation exchange between surfaces 0 and 1 is calculated as follows. The portion of the energy leaving surface 0 and arriving at surface 1 and contributing to the diffuse radiosity is:

$$q_{0 \rightarrow 1}^D = E_{0b} A_0 F_{0 \rightarrow 1} (1 - \tau_{1D} - \tau_{1S} - \rho_{1S})$$

The diffuse energy leaving surface 1 and arriving at surface 0 is:

$$q_{1 \rightarrow 0}^D = J_{1D}^{\text{out}} A_1 F_{1 \rightarrow 0}$$

Using the reciprocity relation $A_1 F_{1 \rightarrow 0} = A_0 F_{0 \rightarrow 1}$ and $F_{1 \rightarrow 0} = 1$. The net radiation exchange is:

$$q_{01}^D = q_{0 \rightarrow 1}^D - q_{1 \rightarrow 0}^D = \frac{E_{0b} J_{1D}^{\text{out}} / (1 - \tau_{1D} - \tau_{1S} - \rho_{1S})}{1/A_1 (1 - \tau_{1D} - \tau_{1S} - \rho_{1S})} \quad (2A9)$$

The space resistance is denoted by:

$$R_3 = 1/A_1 (1 - \tau_{1D} - \tau_{1S} - \rho_{1S})$$

The diffuse radiation of surface 1 for the outer side is:

$$J_{1D}^{\text{out}} = \epsilon_1 E_{1b} + \rho_{1D} G_1^{\text{out}} \quad (2A10)$$

where G_1^{out} is the irradiation of the outer side of surface 1 and

E_{1b} is the thermal emissive power of surface 1, $E_{1b} = \sigma T_1^4$.

The net radiation leaving the surface is:

$$q_1^{\text{out net}} = A_1 (\epsilon_1' E_{1b} - \alpha_1' G_1^{\text{out}})$$

From Eqn. (2A10),

$$G_1^{\text{out}} = \frac{J_{1D}^{\text{out}} - \epsilon_1' E_{1b}}{\rho_{1D}}$$

Therefore

$$q_1^{\text{out net}} = \frac{E_{1b} - J_{1D}^{\text{out}} / (1 - \tau_{1D} - \tau_{1S} - \rho_{1S})}{\rho_{1D} / A_1 \epsilon_1' (1 - \tau_{1D} - \tau_{1S} - \rho_{1S})} \quad (2A11)$$

The surface resistance is denoted by:

$$R_4 = \rho_{1D} / A_1 \epsilon_1' (1 - \tau_{1D} - \tau_{1S} - \rho_{1S})$$

The net radiation leaving the inner side of surface 1 is calculated similarly.

$$q_1^{\text{in net}} = \frac{E_{1b} - J_{1D}^{\text{in}} / (1 - \tau_{1D} - \tau_{1S} - \rho_{1S})}{\rho_{1D} / A_1 \epsilon_1' (1 - \tau_{1D} - \tau_{1S} - \rho_{1S})} \quad (2A12)$$

The surface resistance is the same as for the outer side

R_4 . Using a similar analysis, the space resistance, R_7 , between the receiver pipe and the inner cover can be given as:

$$R_7 = 1/A_3 (1 - \tau_{2S} - \tau_{2D} - \rho_{2S})$$

The surface resistances of the inner and outer sides of surface 2 are:

$$R_6 = \rho_{2D}/A_2 \epsilon_2' (1 - \tau_{2S} - \tau_{2D} - \rho_{2S})$$

The radiation exchange between surfaces 1 and 2 is calculated as follows.

The portion of energy leaving surface 1, arriving at cover 2 and contributing to the diffuse radiosity is:

$$q_{1 \rightarrow 2}^D = J_{1D}^{\text{in}} A_1 F_{1 \rightarrow 2} (1 - \tau_{2S} - \tau_{2D} - \rho_{2S})$$

Similarly, the portion of energy leaving surface 2, arriving at surface 1 and contributing to the diffuse radiosity is:

$$q_{2 \rightarrow 1}^D = J_{2D}^{\text{out}} A_2 F_{2 \rightarrow 1} (1 - \tau_{1S} - \tau_{1D} - \rho_{1S})$$

By using the reciprocity relation,

$$A_1 F_{1 \rightarrow 2} = A_2 F_{2 \rightarrow 1}$$

and

$$F_{2 \rightarrow 1} = 1.$$

The net radiation exchange between surfaces 1 and 2 is:

$$q_{12}^D = \frac{J_{1D}^{\text{in}} / (1 - \tau_{1S} - \tau_{1D} - \rho_{1S}) - J_{2D}^{\text{out}} / (1 - \tau_{2S} - \tau_{2D} - \rho_{2S})}{1/A_2 (1 - \tau_{1S} - \tau_{1D} - \rho_{1S}) (1 - \tau_{2S} - \tau_{2D} - \rho_{2S})} \quad (2A13)$$

The space resistance is denoted by:

$$R_5 = 1/A_2 (1 - \tau_{1S} - \tau_{1D} - \rho_{1S}) (1 - \tau_{2S} - \tau_{2D} - \rho_{2S})$$

The specular transmitted radiation exchange between surfaces 0 and 2 is calculated as follows:

The portion of energy leaving surface 0, arriving at surface 2 and contributing to the diffuse radiosity is:

$$q_{0 \rightarrow 2}^D = E_{0b} A_0 F_{0 \rightarrow 2} \tau_{1S} (1 - \tau_{2S} - \tau_{2D} - \rho_{2S})$$

The diffuse energy leaving surface 2 and arriving at surface 0 is:

$$q_{2 \rightarrow 0}^D = J_{2D}^{\text{out}} A_2 F_{2 \rightarrow 0} \tau_{1S}$$

Using the reciprocity relation,

$$A_0 F_{0 \rightarrow 2} = A_2 F_{2 \rightarrow 0}$$

and

$$F_{2 \rightarrow 0} = 1.$$

The net radiation exchange is given as:

$$q_{02}^S = \frac{E_{0b} - J_{2D}^{\text{out}} / (1 - \tau_{2S} - \tau_{2D} - \rho_{2S})}{1/A_2 \tau_{1S} (1 - \tau_{2S} - \tau_{2D} - \rho_{2S})} \quad (2A14)$$

The space resistance is denoted by:

$$R_g = 1/A_2 \tau_{1S} (1 - \tau_{2S} - \tau_{2D} - \rho_{2S})$$

For the diffuse transmission between surfaces 0 and 2, the energy leaving surface 0 and transmitted diffusely through surface 1 is:

$$E_{0b} A_0 F_{0 \rightarrow 1} \tau_{1D}$$

The portion of this radiation, arriving at surface 2 and contributing to the diffuse radiosity is:

$$q_{0 \rightarrow 2}^D = E_{0b} A_0 F_{0 \rightarrow 1} F_{1 \rightarrow 2} \tau_{1D} (1 - \tau_{2S} - \tau_{2D} - \rho_{2S})$$

The radiation leaving surface 2 and diffusely transmitted through surface 1 is:

$$q_{2 \rightarrow 0}^D = J_{2D}^{\text{out}} A_2 F_{2 \rightarrow 1} F_{1 \rightarrow 0} \tau_{1D}$$

Using the reciprocity relations,

$$A_0 F_{0 \rightarrow 1} = A_1 F_{1 \rightarrow 0}$$

$$A_1 F_{1 \rightarrow 2} = A_2 F_{2 \rightarrow 1}$$

and

$$F_{1 \rightarrow 0} = F_{2 \rightarrow 1} = 1$$

The net diffuse transmitted radiation is:

$$q_{02}^D = \frac{E_{0b} - J_{2D}^{\text{out}} / (1 - \tau_{2S} - \tau_{2D} - \rho_{2S})}{1/A_2 \tau_{1D} (1 - \tau_{2S} - \tau_{2D} - \rho_{2S})} \quad (2A15)$$

The space resistance is denoted by:

$$R_g = 1/A_2 \tau_{1D} (1 - \tau_{2S} - \tau_{2D} - \rho_{2S})$$

Using a similar analysis, the space resistances for specular and diffuse transmitted radiation between surfaces 1 and 3 are given as:

$$R_{10} = 1/A_3 \tau_{2D} (1 - \tau_{1S} - \tau_{1D} - \rho_{1S})$$

$$R_{11} = 1/A_3 \tau_{2S} (1 - \tau_{1S} - \tau_{1D} - \rho_{1S})$$

The surface resistance of surface 3 is calculated as follows:

The radiosity of surface 3 is:

$$J_3 = \epsilon'_3 E_{3b} + \rho'_3 G_3 =$$

$$G_3 = \frac{J'_3 - \epsilon'_3 E_{3b}}{\rho'_3}$$

The net energy leaving surface 3 is the difference between the radiosity and the irradiosity of the surface:

$$q_{3, \text{net}} = A_3 (J_3 - G_3) = \frac{E_{3b} - J_3}{(1 - \epsilon'_3) / \epsilon'_3 A_3} \quad (2A16)$$

The surface resistance is denoted by:

$$R_{12} = (1 - \epsilon'_3) / \epsilon'_3 A_3$$

The complete network diagram is given in Fig. 2A2.

The net radiation exchanges within the system are shown in the network diagram.

For cover 1:

$$q_{l,1} = \frac{B-C}{R_4} + \frac{D-C}{R_4} \quad (2A17)$$

For cover 2:

$$q_{l,2} = \frac{E-F}{R_6} + \frac{G-F}{R_6} \quad (2A18)$$

For the receiver tube:

$$q_{l,3} = \frac{H-I}{R_{12}} \quad (2A19)$$

The unknowns in the above three equations are B, D, E, G and H.

The energy balance at node B is:

$$\frac{A-B}{R_3} + \frac{C-B}{R_4} = 0 \quad (2A20)$$

The energy balance at node D is:

$$\frac{C-D}{R_4} + \frac{E-D}{R_5} + \frac{H-D}{R_{2eq}} = 0 \quad (2A21)$$

The energy balance at node E is:

$$\frac{D-E}{R_5} + \frac{F-E}{R_6} + \frac{A-E}{R_{1eq}} = 0 \quad (2A22)$$

The energy balance at node G is:

$$\frac{F-G}{R_6} + \frac{H-G}{R_7} = 0 \quad (2A23)$$

The energy balance at node H is:

$$\frac{A-H}{R_{3eq}} + \frac{D-H}{R_{2eq}} + \frac{G-H}{R_7} + \frac{I-H}{R_{12}} = 0 \quad (2A24)$$

By solving this system, it can be shown that:

$$B = \frac{R_3 C + R_4 A}{R_3 + R_4} \quad (2A25)$$

$$D = \frac{\theta_1}{\theta_2}$$

(2A26)

where

$$\theta_1 = \frac{C}{R_4} + \frac{\theta_4}{\theta_3 R_5} + \frac{\theta_5}{\theta_6 R_{2eq}}$$

$$\theta_2 = \frac{1}{R_4} + \frac{1}{R_5} - \frac{1}{\theta_3 R_5^2} + \frac{-1 + \theta_6 R_{2eq}}{\theta_6 R_{2eq}^2}$$

$$\theta_3 = \frac{1}{R_5} + \frac{1}{R_6} + \frac{1}{R_{1eq}}$$

$$\theta_4 = \frac{F}{R_6} + \frac{A}{R_{1eq}}$$

$$\theta_5 = \frac{A}{R_{3eq}} + \frac{F}{R_6 + R_7} + \frac{I}{R_{12}}$$

$$\theta_6 = \frac{1}{R_{3eq}} + \frac{1}{R_{2eq}} + \frac{1}{R_6 + R_7} + \frac{1}{R_{12}}$$

$$H = \frac{\theta_2 \theta_5 R_{2eq} \theta_1}{\theta_2 \theta_6 R_{2eq}}$$

(2A27)

$$E = \frac{\theta_1 + \theta_2 \theta_4 R_5}{\theta_2 \theta_3 R_5}$$

(2A28)

$$G = \frac{H R_6 + F R_7}{R_6 + R_7}$$

(2A29)

B. RADIATION EXCHANGE IN THE SOLAR WAVELENGTH BETWEEN THE SURFACES OF THE ABSORBER AND THE SUN (FIRST CONFIGURATION WITH TWO GLASS COVERS)

The radiation analysis will be based on the assumptions listed in Section 4.1.7 and has as follows.

The energy leaving surface 0 and arriving at surface 3 is (see Fig. 2A-3):

$$q_{0 \rightarrow 3} = \text{SRI} \tau_1 \tau_2$$

The energy leaving surface 3 and arriving at surface 0 is:

$$q_{3 \rightarrow 0} = J_3 A_3 \tau_1 \tau_2$$

The net radiation is:

$$q_{03} = q_{0 \rightarrow 3} - q_{3 \rightarrow 0} = \frac{\text{SRI} - J_3 A_3}{1/\tau_1 \tau_2} \quad (2B1)$$

The space-resistance between surfaces 0 and 3 is denoted by (see network diagram Fig. 4.14):

$$R_1 = 1/\tau_1 \tau_2$$

The radiation exchange between surfaces 0 and 1 has as follows.

The radiation leaving surface 0 and arriving at surface 1 is:

$$q_{0 \rightarrow 1} = \text{SRI} (1 - \tau_1)$$

The radiation leaving surface 1 and arriving at surface 0 is:

$$q_{1 \rightarrow 0} = J_1^{\text{out}} A_1$$

where J_1^{out} is the radiosity of the outer side of surface 1.

The net radiation is:

$$q_{01} = q_{0 \rightarrow 1} - q_{1 \rightarrow 0} = \frac{\text{SRI} - J_1^{\text{out}} A_1 / (1 - \tau_1)}{1 / (1 - \tau_1)} \quad (2B2)$$

The space resistance is denoted by:

$$R_2 = 1 / (1 - \tau_1).$$

The radiosity of the outer side of surface 1 is:

$$J_1^{\text{out}} = \rho_1 G_1^{\text{out}}$$

where G_1^{out} is the irradiosity of the outer side of surface 1.

The net radiation arriving at the outer side of surface 1 is:

$$q_1^{\text{out net}} = A_1 \alpha_1 G_1^{\text{out}}$$

or

$$q_1^{\text{out net}} = A_1 \alpha_1 \frac{J_1^{\text{out}}}{\rho_1} = \frac{A_1 J_1^{\text{out}} / (1 - \tau_1)}{\rho_1 / \epsilon_1 (1 - \tau_1)} \quad (2B3)$$

The surface resistance is denoted by:

$$R_3 = \rho_1 / \epsilon_1 (1 - \tau_1).$$

Using a similar analysis, the surface resistance for the inner side is found as:

$$R_3 = \rho_1 / \epsilon_1 (1 - \tau_1)$$

The radiation exchange between surfaces 2 and 3 is as follows.

The energy leaving surface 2 and arriving at surface 3 is:

$$q_{2 \rightarrow 3} = J_2^{\text{in}} A_2$$

The energy leaving surface 3 and arriving at surface 2 is:

$$q_{3 \rightarrow 2} = J_3 A_3 (1 - \tau_2)$$

The net radiation exchange is:

$$q_{23} = q_{2 \rightarrow 3} - q_{3 \rightarrow 2} = \frac{J_2^{\text{in}} A_2 / (1 - \tau_2) - J_3 A_3}{1 / (1 - \tau_2)} \quad (2B4)$$

The space resistance is denoted by:

$$R_6 = 1 / (1 - \tau_2).$$

The net radiation arriving at the inner surface of cover 2 is calculated in the same manner as for surface 1:

$$q_2^{\text{in net}} = \frac{A_2 J_2^{\text{in}} / (1 - \tau_2)}{\rho_2 / \epsilon_2 (1 - \tau_2)} \quad (2B5)$$

The surface resistance is denoted by:

$$R_5 = \rho_2 / \epsilon_2 (1 - \tau_2)$$

The net radiation arriving at the outer side of surface 2 is:

$$q_2^{\text{out net}} = \frac{A_2 J_2^{\text{out}} / (1 - \tau_2)}{\rho_2 / \epsilon_2 (1 - \tau_2)} \quad (2B6)$$

The surface resistance of the outer side is:

$$R_5 = \rho_2 / \epsilon_2 (1 - \tau_2).$$

The net radiation exchange between surfaces 1 and 2 is as follows.

The energy leaving surface 1 and arriving at surface 2 is:

$$q_{1 \rightarrow 2} = J_1^{\text{in}} A_1 (1 - \tau_2)$$

The energy leaving surface 2 and arriving at surface 1 is:

$$q_{2 \rightarrow 1} = J_2^{\text{out}} A_2 (1 - \tau_1)$$

The net radiation exchange is:

$$q_{12} = q_{1 \rightarrow 2} - q_{2 \rightarrow 1} = \frac{J_1^{\text{in}} A_1 / (1 - \tau_1) - J_2^{\text{out}} A_2 / (1 - \tau_2)}{1 / (1 - \tau_1) (1 - \tau_2)} \quad (2B7)$$

The space resistance is:

$$R_4 = 1 / (1 - \tau_1) (1 - \tau_2).$$

The net radiation exchange between surfaces 0 and 2 is calculated as follows.

The energy leaving surface 0 and arriving at surface 2 is:

$$q_{0 \rightarrow 2} = S R I \tau_1 (1 - \tau_2).$$

The energy leaving surface 2 and arriving at surface 0 is:

$$q_{2 \rightarrow 0} = J_2^{\text{out}} A_2 \tau_1$$

The net radiation exchange is:

$$q_{02} = q_{0+2} - q_{2+0} = \frac{SRI - J_2^{\text{out}} A_2 / (1 - \tau_2)}{1/\tau_1 (1 - \tau_2)} \quad (2B8)$$

The space resistance is:

$$R_7 = 1/\tau_1 (1 - \tau_2).$$

Using a similar analysis, the space resistance between surfaces 3 and 1 is:

$$R_8 = 1/\tau_2 (1 - \tau_1).$$

The radiosity of surface 3 is:

$$J_3 = \rho_3 G_3.$$

The net radiation arriving at surface 3 is:

$$q_3^{\text{net}} = A_3 \alpha_3 G_3$$

or

$$q_3^{\text{net}} = \frac{A_3 J_3}{\rho_3 / \epsilon_3} \quad (2B9)$$

The surface resistance is denoted by:

$$R_9 = \rho_3 / \epsilon_3$$

The net solar gain of each surface is (see network diagram

Fig. 2A.4) :

$$q_{s,1} = \frac{B-C}{R_3} + \frac{D-C}{R_3}$$

$$q_{s,2} = \frac{E-F}{R_5} + \frac{G-F}{R_5}$$

$$q_{s,3} = \frac{H-I}{R_9}$$

but $C=F=I=0$; therefore

$$q_{s,1} = \frac{B+D}{R_3} \quad (2B10)$$

$$q_{s,2} = \frac{E+G}{R_5} \quad (2B11)$$

$$q_{s,3} = \frac{H}{R_9} \quad (2B12)$$

The unknowns in the above three equations are B, D, E, G, and H.

The energy balance at node B is:

$$\frac{A-B}{R_2} - \frac{B}{R_3} = 0 \quad (2B13)$$

The energy balance at node D is:

$$-\frac{D}{R_3} + \frac{E-D}{R_4} + \frac{H-D}{R_8} = 0 \quad (2B14)$$

The energy balance at node E is:

$$\frac{D-E}{R_4} - \frac{E}{R_5} + \frac{A-E}{R_7} = 0 \quad (2B15)$$

The energy balance at node G is:

$$-\frac{G}{R_5} + \frac{H-G}{R_6} = 0 \quad (2B16)$$

The energy balance at node H is:

$$\frac{A-H}{R_1} + \frac{D-H}{R_8} + \frac{G-H}{R_6} - \frac{H}{R_9} = 0 \quad (2B17)$$

By solving this system, it can be shown that:

$$B = \frac{R_3 A}{R_2 + R_3} \quad (2B18)$$

$$D = \frac{\theta_1}{\theta_2} \quad (2B19)$$

where $A = SRT$

$$\theta_1 = \frac{\theta_4}{\theta_3 R_4} + \frac{\theta_5}{\theta_6 R_8}$$

$$\theta_2 = \frac{1}{R_3} + \frac{1}{R_4} - \frac{1}{\theta_3 R_4^2} + \frac{-1 + \theta_6 R_8}{\theta_6 R_8^2}$$

$$\theta_3 = \frac{1}{R_4} + \frac{1}{R_5} + \frac{1}{R_7}$$

$$\theta_4 = \frac{A}{R_7}$$

$$\theta_5 = \frac{A}{R_1}$$

$$\theta_6 = \frac{1}{R_1} + \frac{1}{R_8} + \frac{1}{R_5 + R_6} + \frac{1}{R_9}$$

$$H = \frac{\theta_2 \theta_5 R_8 + \theta_1}{\theta_2 \theta_6 R_8} \quad (2B20)$$

$$E = \frac{\theta_1 + \theta_2 \theta_4 R_4}{\theta_2 \theta_3 R_4} \quad (2B21)$$

$$G = \frac{HR_5}{R_5 + R_6} \quad (2B22)$$

Surface

- 0 - Environment
- 1 - Outer glass cover
- 2 - Inner glass cover
- 3 - Receiver tube

Figure 2A-1 Cross-section of the absorber pipe and the surface of the environment (first configuration with two glass covers) .

Surface

- 0 - Reflector
- 1 - Outer glass cover
- 2 - Inner glass cover
- 3 - Receiver tube

Figure 2A-3 Cross-section of the absorber pipe and the reflector surface (first configuration with two glass covers) .

Where $A = J_0 = E_{0b}$ - Surface of the environment
 $B = J_{1D}^{out} / (1 - \tau_{1s} - \tau_{1D} - \rho_{1s})$ - Outer side of outer cover
 $C = E_{1h}$ - Outer cover
 $D = J_{1D}^{in} / (1 - \tau_{1s} - \tau_{1D} - \rho_{1s})$ - Inner side of outer cover
 $E = J_{2D}^{out} / (1 - \tau_{2s} - \tau_{2D} - \rho_{2s})$ - Outer side of Inner cover
 $F = E_{2b}$ - Inner cover
 $G = J_{2h}^{in} / (1 - \tau_{2s} - \tau_{2D} - \rho_{2s})$ - Inner side of inner cover
 $H = J_3$ - Outer side of receiver pipe
 $I = E_{3h}$

$$\begin{aligned}
 R_1 &= 1/A_3 \tau_{1s} \tau_{2s} & R_7 &= 1/A_3 (1 - \tau_{2s} - \tau_{2D} - \rho_{2s}) \\
 R_2 &= 1/A_3 \tau_{1D} \tau_{2D} & R_8 &= 1/A_2 \tau_{1s} (1 - \tau_{2s} - \tau_{2D} - \rho_{2s}) \\
 R_3 &= 1/A_1 (1 - \tau_{1s} - \tau_{1D} - \rho_{1s}) & R_9 &= 1/A_2 \tau_{1D} (1 - \tau_{2s} - \tau_{2D} - \rho_{2s}) \\
 R_4 &= \rho_{1D}/A_1 \epsilon_1 (1 - \tau_{1s} - \tau_{1D} - \rho_{1s}) & R_{10} &= 1/A_3 \tau_{2D} (1 - \tau_{1s} - \tau_{1D} - \rho_{1s}) \\
 R_5 &= 1/A_2 (1 - \tau_{1s} - \tau_{1D} - \rho_{1s}) (1 - \tau_{2s} - \tau_{2D} - \rho_{2s}) & R_{11} &= 1/A_3 \tau_{2s} (1 - \tau_{1s} - \tau_{1D} - \rho_{1s}) \\
 R_6 &= \rho_{2D}/A_2 \epsilon_2' (1 - \tau_{2s} - \tau_{2D} - \rho_{2s}) & R_{12} &= (1 - \epsilon_3')/A_3 \epsilon_3' \\
 R_{1eq} &= R_8 R_9 / (R_8 + R_9) & R_{3eq} &= R_1 R_2 / (R_1 + R_2) \\
 R_{2eq} &= R_{10} R_{11} / (R_{10} + R_{11})
 \end{aligned}$$

Figure 2A.2 Network diagram showing radiation exchanges in the long wave length region (first configuration with two glass covers)

Where

- A = SRI - Reflector surface
- B = $J_1^{\text{out}} A_1 / (1 - \tau_1)$ - Outer side of outer cover
- C = 0 - Outer cover
- D = $J_1^{\text{in}} A_1 / (1 - \tau_1)$ - Inner side of outer cover
- E = $J_2^{\text{out}} A_2 / (1 - \tau_2)$ - Outer side of inner cover
- F = 0 - Inner cover
- G = $J_2^{\text{in}} A_2 / (1 - \tau_2)$ - Inner side of inner cover
- H = $J_3 H_3$ - Outer side of receiver pipe
- I = 0 - Receiver pipe

$$\begin{aligned}
 R_1 &= 1 / \tau_1 \tau_2 \\
 R_2 &= 1 / (1 - \tau_1) \\
 R_3 &= \rho_1 / \epsilon_1 (1 - \tau_1) \\
 R_4 &= 1 / (1 - \tau_1) (1 - \tau_2) \\
 R_5 &= \rho_2 / \epsilon_2 (1 - \tau_2) \\
 R_6 &= 1 / (1 - \tau_2) \\
 R_7 &= 1 / \tau_1 (1 - \tau_2) \\
 R_8 &= 1 / \tau_2 (1 - \tau_1) \\
 R_9 &= \rho_2 / \epsilon_2
 \end{aligned}$$

Figure 2A.4 Network diagram showing radiation exchange in the solar wave length region (first configuration with two glass covers).

LIST OF INPUT USED IN COMPUTER PROGRAMS 3 THROUGH 8

Appendices 3 through 8 are used to calculate the performance of the absorbers under consideration. The input variables are summarized below. (Note that only part of these are used in each program.)

TSL1 = τ_{1S}	AL = l_c	m
TDL1 = τ_{1D}	DIV = Δx	m
TSL2 = τ_{2S}	D1 = D_1	m
TDL2 = τ_{2D}	D2 = D_2	m
RSL1 = ρ_{1S}	D3 = D_3	m
RSL2 = ρ_{2S}	DI1 = D_{lin}	m
RDL1 = ρ_{1D}	DI2 = D_{2in}	m
RDL2 = ρ_{2D}	DI3 = D_{3in}	m
ABL1 = α'_1	DP = d_p	m
ABL2 = α'_2	TFIN = T_f in	K
ABL3 = α'_3	RM = ρ_r	
REL3 = ρ'_3	SR = I_D	w/m ²
TRS1 = τ_1	TAIR = T_a	K
TRS2 = τ_2	APER = a	m
RES1 = ρ_1	WFR = $\dot{V}$	m ³ /hr
RES2 = ρ_2	VAIR = W	km/hr
ABS1 = α_1	FINT = F_{opt}	
ABS2 = α_2	X(1) = T_1	K
RES3 = ρ_3	X(2) = T_2	K
ABS3 = α_3	X(3) = T_3	K

PS = Pressure in evacuated space atm (Appendix 5)

PR = Initial pressure, atm (Appendix 8)

The computer program outputs are listed at the beginning of each appendix.

APPENDIX 4

COMPUTER PROGRAM TO CALCULATE THE PERFORMANCE
OF THE ABSORBER OF THE FIRST CONFIGURATION
WITH ONE GLASS COVER

The outputs of this computer program are:

- a) Glass temperature
- b) Receiver temperature
- c) Inlet water temperature
- d) Outlet water temperature
- e) Thermal efficiency

```

DIMENSION X(2),WA(8),PAR(27)
EXTERNAL AUX
DOUBLE PRECISION AUX,X,WA,PAR,EPS
READ*, TSL1,TDL1,RSL1,RDL1,ABL1,ABL2,REL2,TRS1,
1RES1,ABS1,RES2,ABS2
*READ*, AL,DIU,D1,D2,DI2,TFIN,RH,SR,TAIR,APER,
1WFR,VAIR,FINT
READ*, X(1),X(2)
EPS=1.0D-6
NSIG=5
N=2
ITHAX=500
PAR(1)=TSL1
PAR(2)=TDL1
PAR(3)=RSL1
PAR(4)=RDL1
PAR(5)=ABL1
PAR(6)=ABL2
PAR(7)=REL2
PAR(8)=TRS1
PAR(9)=RES1
PAR(10)=ABS1
PAR(11)=RES2
PAR(12)=ABS2
PAR(13)=AL
PAR(14)=DIU
PAR(15)=D1
PAR(16)=D2
PAR(17)=DI2
PAR(18)=TFIN
PAR(19)=RH
PAR(20)=SR
PAR(21)=TAIR
PAR(22)=APER
PAR(23)=WFR
PAR(24)=VAIR
PAR(25)=FINT
PAR(26)=0
PAR(27)=0
I=1
40 CONTINUE
CALL ZSYSTH(AUX,EPS,NSIG,N,X,ITHAX,WA,PAR,IER)
ITHAX=500
PRINT*, '*****'
PRINT '(7,T10,A,I2)', 'STEP=',I
PRINT '(4,T10,A,F10.5)', 'GLASS TEMP=',X(1)
PRINT '(7,T10,A,F10.5)', 'RECEIVER TEMP=',X(2)
PRINT '(7,T10,A,F10.5)', 'WATER TEMP. IN=',PAR(18)
PRINT '(7,T10,A,F10.5)', 'WATER TEMP. OUT=',PAR(28)
PRINT '(7,T10,A,F6.4)', 'THERMAL EFFICIENCY=',PAR(27)
I=I+1
KA=(AL/DIU)+1.
IF(I.EQ.KA) GO TO 70
PAR(18)=PAR(28)
GO TO 40
70 CONTINUE
STOP
END

```

```

FUNCTION AUX(X,K,PAR)
DIMENSION X(2),PAR(27)
DOUBLE PRECISION AUX,X,PAR
PI=3.14159
A1=PI*PAR(15)*PAR(14)
A2=PI*PAR(16)*PAR(14)
RSKY=5.26333E-13*PAR(21)**6.0
EB1=5.669E-8*X(1)**4.0
EB2=5.669E-3*X(2)**4.0
R1=1.0/(A2*PAR(1))
R2=1.0/(A2*PAR(2))
REQ=R1*R2/(R1+R2)
R3=1.0/(A1*(1.0-PAR(1)-PAR(2)-PAR(3)))
R4=PAR(4)/(A1*PAR(5)*(1.0-PAR(1)-PAR(2)-PAR(3)))
RS=R4
R6=1.0/(A2*(1.0-PAR(1)-PAR(2)-PAR(3)))
R7=(1.0-PAR(6))/(A2*PAR(6))
B=(RSKY*R4+EB1*R3)/(R4+R3)
E=(RSKY/REQ+EB2/R7+EB1/(R5+R6))/(1.0/REQ+1.0/R6+
11.0/R7-R5/(R6*(R5+R6)))
D=(EB1*R6+E*RS)/(R5+R6)
QL1=(B-EB1)/R4+(D-EB1)/R5
QL2=(E-EB2)/R7
RS1=1.0/PAR(8)
RS2=1.0/(1.0-PAR(8))
RS3=PAR(9)/(PAR(10)*(1.0-PAR(8)))
RS4=RS3
RS5=RS2
RS6=PAR(11)/PAR(12)
SRI=PAR(20)*PAR(19)*PAR(25)*PAR(14)*((PAR(22)-
1PAR(15))+(PAR(15)-PAR(16))*PAR(8)**2)+PAR(20)*PAR(
214)*PAR(16)
BS=(SRI*RS3)/(RS2+RS3)
ES=(SRI/RS1)/(1.0/RS1+1.0/RS5+1.0/RS6-RS4/(
1RS5*(RS4+RS5)))
DS=(ES*RS4)/(RS4+RS5)
QS1=(BS+DS)/RS3
QS2=ES/RS6
TKALT=2.59E-2
VALT=15.06E-6
RELT=0.2778*PAR(24)*PAR(15)/VALT
IF(RELT.LT.1000.0) GO TO 20
IF(RELT.GT.1000.0) GO TO 30
20 SULT=0.4+0.54*RELT**0.52
GO TO 35
30 SULT=0.3*RELT**0.6
35 CONTINUE
QCLT=A1*TKALT*SULT*(PAR(21)-X(1))/PAR(15)
IF(PAR(18).LT.373) GO TO 36
IF(PAR(18).GT.373) GO TO 37
36 DVIW=3.361E-9*EXP(1660/PAR(18))
DMIW=1.88E-6*EXP(1872/PAR(18))
GO TO 38
37 DVIW=1.532E-8*EXP(1103/PAR(18))
DMIW=8.84E-6*EXP(1288/PAR(18))
38 CONTINUE
TKW=66.8E-2
PRW=2.55
CPU=4000
IF(X(2).LT.373) GO TO 41

```

```

      IF(X(2).GT.373) GO TO 42
41 DMIWL=1.88E-6*EXP(1872/X(2))
   GO TO 43
42 DMIWL=8.84E-6*EXP(1288/X(2))
43 CONTINUE
   REW=4.0*PAR(23)/(PI*PAR(17)*3600.0*DVIW)
   IF(REW.LT.2100) GO TO 44
   IF(REW.LT.5000) GO TO 45
   IF(REW.GT.5000) GO TO 46
44 SU=(48.0/11.0)+(0.0668*(PAR(17)/PAR(14))*REW*PRW)
   1/(1.0+0.04*((PAR(17)/PAR(14))*REW*PRW)**0.67)
   GO TO 47
45 SU=0.166*(REW**0.67-125)*PRW**0.33*(1.0+
   1*(PAR(17)/PAR(14))*0.67)*(DMIW/DMIWL)**0.14
   GO TO 47
46 FR=(1.82*LOG10(REW)-1.64)**(-2)
   SU=((FR/8.0)*REW*PRW)/((1.07+12.7*((FR/8.0)**0.5))*
   1*(PRW**0.67-1.0))
47 CONTINUE
   HTC=SU*TKU/PAR(17)
   AP=3.6*HTC*PI*PAR(17)/(PAR(23)*CPW)
   PAR(26)=PAR(18)*EXP(-AP*PAR(14))+X(2)*(1.0-
   1*EXP(-AP*PAR(14)))
   PAR(27)=(PAR(26)-PAR(18))*PAR(23)*CPW/(3.6*PAR(20)
   1*PAR(14)*PAR(22))
   FMT=X(2)+(PAR(18)-X(2))*(1.0-EXP(-AP*PAR(14)))/
   1*(AP*PAR(14))
   QDEL=HTC*PI*PAR(17)*PAR(14)*(FMT-X(2))
   GO TO (50,60) K
50 AUX=QL2+QS2+QDEL
   RETURN
60 AUX=QL1+QS1+QCLT
   RETURN
   END

```


APPENDIX 5

COMPUTER PROGRAM TO CALCULATE THE PERFORMANCE
OF THE ABSORBER OF THE FIRST CONFIGURATION
WITH TWO GLASS COVERS

The outputs of this computer program are:

- a) Outer glass temperature
- b) Inner glass temperature
- c) Receiver temperature
- d) Inlet water temperature
- e) Outlet water temperature
- f) Thermal efficiency

```

DIMENSION X(3),WA(14),PAR(36)
EXTERNAL AUX
DOUBLE PRECISION AUX,X,WA,PAR,EPS
READ*,TSL1,TSL2,TDL1,TDL2,RSL1,RSL2,RDL1,RDL2,
1ABL1,ABL2,ABL3,REL3,TRS1,TRS2,RES1,RES2,ABS1,
2ABS2,RES3,ABS3
READ*,AL,DIU,D1,D2,D3,DI3,TFIN,RH,SR,TAIR,APER,
1WFR,VAIR,FINT
READ*, X(1),X(2),X(3)
EPS=1.0D-2
NSIG=2
N=3
ITMAX=500
PAR(1)=TSL1
PAR(2)=TSL2
PAR(3)=TDL1
PAR(4)=TDL2
PAR(5)=RSL1
PAR(6)=RSL2
PAR(7)=RDL1
PAR(8)=RDL2
PAR(9)=ABL1
PAR(10)=ABL2
PAR(11)=ABL3
PAR(12)=REL3
PAR(13)=TRS1
PAR(14)=TRS2
PAR(15)=RES1
PAR(16)=RES2
PAR(17)=ABS1
PAR(18)=ABS2
PAR(19)=RES3
PAR(20)=ABS3
PAR(21)=AL
PAR(22)=DIU
PAR(23)=D1
PAR(24)=D2
PAR(25)=D3
PAR(26)=DI3
PAR(27)=TFIN
PAR(28)=RH
PAR(29)=SR
PAR(30)=TAIR
PAR(31)=APER
PAR(32)=WFR
PAR(33)=VAIR
PAR(34)=FINT
PAR(35)=0.0
PAR(36)=0.0
I=1
40 CONTINUE
ITMAX=500
CALL ZSYSTEM(AUX,EPS,NSIG,N,X,ITMAX,WA,PAR,IER)
PRINT*, '*****'
PRINT '(/T10,A,I2)', 'STEP=', I
PRINT '(/T10,A,F10.5)', 'OUTER GLASS TEMP.=', X(1)
PRINT '(/T10,A,F10.5)', 'INNER GLASS TEMP.=', X(2)
PRINT '(/T10,A,F10.5)', 'RECEIVER TEMP.=', X(3)

```

```

PRINT '(/T10,A,F10.5)', 'WATER TEMP. IN=', PAR(27)
PRINT '(/T10,A,F10.5)', 'WATER TEMP. OUT=', PAR(35)
PRINT '(/T10,A,F6.4)', 'THERMAL EFFICIENCY=', PAR(36)
I=I+1
KA=(AL/DIV)+1
IF(I.EQ.KA) GO TO 70
PAR(27)=PAR(35)
GO TO 40
70 CONTINUE
STOP
END
FUNCTION AUX(X,K,PAR)
DIMENSION X(3), PAR(36)
DOUBLE PRECISION AUX,X,PAR
PI=3.14159
A1=PI*PAR(23)*PAR(22)
A2=PI*PAR(24)*PAR(22)
A3=PI*PAR(25)*PAR(22)
RSKY=5.26338E-13*PAR(30)**6.0
EB1=5.669E-8*X(1)**4.0
EB2=5.669E-8*X(2)**4.0
EB3=5.669E-8*X(3)**4.0
R1=1.0/(A3*PAR(1)*PAR(2))
R2=1.0/(A3*PAR(3)*PAR(4))
REQ3=R1*R2/(R1+R2)
HE1=1.0-PAR(1)-PAR(3)-PAR(5)
HE2=1.0-PAR(2)-PAR(4)-PAR(6)
R3=1.0/(A1*HE1)
R4=PAR(7)/(A1*PAR(9)*HE1)
R5=1.0/(A2*HE1*HE2)
R6=PAR(8)/(A2*PAR(10)*HE2)
R7=1.0/(A3*HE2)
R8=1.0/(A2*PAR(1)*HE2)
R9=1.0/(A2*PAR(3)*HE2)
REQ1=R8*R9/(R8+R9)
R10=1.0/(A3*PAR(4)*HE1)
R11=1.0/(A3*PAR(2)*HE1)
REQ2=R10*R11/(R10+R11)
R12=(1.0-PAR(11))/(A3*PAR(11))
Z6=1.0/REQ3+1.0/REQ2+1.0/(R6+R7)+1.0/R12
Z5=RSKY/REQ3+EB2/(R6+R7)+EB3/R12
Z4=EB2/R6+RSKY/REQ1
Z3=1.0/R5+1.0/R6+1.0/REQ1
Z2=1.0/R4+1.0/R5-1.0/(Z3*RS**2)+(Z6*REQ2-1.0)
1/(Z6*REQ2**2)
Z1=EB1/R4+Z4/(Z3*RS)+Z5/(Z6*REQ2)
B=(EB1*R3+RSKY*R4)/(R3+R4)
D=Z1/Z2
H=(Z2*Z5*REQ2+Z1)/(Z2*Z6*REQ2)
E=(Z1+Z2*Z4*RS)/(Z2*Z3*RS)
G=(EB2*R7+H*R6)/(R6+R7)
QL1=(B-EB1)/R4+(D-EB1)/R4
QL2=(E-EB2)/R6+(G-EB2)/R6
QL3=(H-EB3)/R12
RS1=1.0/(PAR(13)*PAR(14))
RS2=1.0/(1.0-PAR(13))
RS3=PAR(15)/(PAR(17)*(1.0-PAR(13)))
RS4=1.0/((1.0-PAR(13))*(1.0-PAR(14)))
RSS=PAR(16)/(PAR(18)*(1.0-PAR(14)))
RS6=1.0/(1.0-PAR(14))

```

```

RS7=1.0/(PAR(13)*(1.0-PAR(14)))
RS8=1.0/(PAR(14)*(1.0-PAR(13)))
RS9=PAR(19)/PAR(20)
SRI=PAR(29)*PAR(28)*PAR(34)*PAR(22)*((PAR(31)-
1*PAR(23))+(PAR(23)-PAR(24))*PAR(13)**2.0+(PAR(24)
2-PAR(25))*PAR(13)*PAR(14))**2)+PAR(29)*PAR(22)
3*PAR(25)
ZS6=1.0/RS1+1.0/RS8+1.0/(RS5+RS6)+1.0/RS9
ZS5=SRI/RS1
ZS4=SRI/RS7
ZS3=1.0/RS4+1.0/RS5+1.0/RS7
ZS2=1.0/RS3+1.0/RS4-1.0/(ZS3*RS4**2.0)+(ZS6*RS8-
11.0)/(ZS6*RS8**2.0)
ZS1=ZS4/(ZS3*RS4)+ZS5/(ZS6*RS8)
BS=SRI*RS3/(RS2+RS3)
DS=ZS1/ZS2
HS=(ZS2*ZS5*RS8+ZS1)/(ZS2*ZS6*RS8)
ES=(ZS2*ZS4*RS4+ZS1)/(ZS2*ZS3*RS4)
GS=HS*RS5/(RS5+RS6)
QS1=(BS+DS)/RS3
QS2=(ES+GS)/RS5
QS3=HS/RS9
TKALT=2.59E-2
VALT=15.06E-6
RELT=0.2778*PAR(33)*PAR(23)/VALT
IF(RELT.LT.1000.0) GO TO 20
IF(RELT.GT.1000.0) GO TO 30
20 SULT=0.4+0.54*RELT**0.52
GO TO 35
30 SULT=0.3*RELT**0.6
35 CONTINUE
QCLT=A1*TKALT*SULT*(PAR(30)-X(1))/PAR(23)
TKW=66.8E-2
IF(PAR(27).LT.373) GO TO 36
IF(PAR(27).GT.373) GO TO 37
36 DVIW=3.361E-9*EXP(1660/PAR(27))
DMIW=1.88E-6*EXP(1872/PAR(27))
GO TO 38
37 DVIW=1.532E-8*EXP(1103/PAR(27))
DMIW=8.84E-6*EXP(1288/PAR(27))
38 CONTINUE
PRW=2.55
CPW=4000
IF(X(3).LT.353) GO TO 41
IF(X(3).GT.353) GO TO 42
41 DMIWL=1.88E-6*EXP(1872/X(3))
GO TO 43
42 DMIWL=8.84E-6*EXP(1288/X(3))
43 CONTINUE
REW=4.0*PAR(32)/(PI*PAR(26)*360.0*DVIW)
IF(REW.LT.2100) GO TO 44
IF(REW.LT.5000) GO TO 45
IF(REW.GT.5000) GO TO 46
44 SU=(48.0/11.0)+(0.0668*(PAR(26)/PAR(22))*REW*PRW)/
1(1.0+0.04*((PAR(26)/PAR(22))*REW*PRW)**0.67)
GO TO 47
45 SU=0.166*(REW**0.67-125)*PRW**0.33*(1.0+(PAR(26)
1/PAR(22))**0.67)*(DMIW/DMIWL)**0.14
GO TO 47
46 FR=(1.82*LOG10(REW)-1.64)**(-2)

```

```

SU=((FR/8.0)*REW*PRW)/((1.07+12.7*((FR/8.0)**0.5))
2*(PRW**0.67-1.0))
47 CONTINUE
HTC=SU*TKW/PAR(26)
AP=3.6*HTC*PI*PAR(26)/(PAR(32)*CPW)
FHT=X(3)+(PAR(27)-X(3))*(1.0-EXP(-AP*PAR(22)))
1/(AP*PAR(22))
QDEL=HTC*PI*PAR(26)*PAR(22)*(FHT-X(3))
TKHT=0.002528*(ABS(X(3)+X(2))/2.0)**1.5/((X(3)+X(2))/
12.0+200)
AF=200.0/(X(3)+X(2))
GRPR=2737*((1.0+2.0*AF)**2.0)*(AF**4.0)*ABS(X(3)
1-X(2))*(50*(PAR(24)-PAR(25))**3.0
ECK=0.18*(GRPR)**0.25
IF(ECK.GT.1.0) GO TO 50
ECK=1.0
50 CONTINUE
QKCH=(A3+A2)*TKHT*ECK*(X(3)-X(2))/(PAR(24)-PAR(25))
PAR(35)=PAR(27)*EXP(-AP*PAR(22))+X(3)*(1.0-EXP(-
1AP*PAR(22)))
PAR(36)=(PAR(35)-PAR(27))*PAR(32)*CPW/(3.6*PAR(29)*
1PAR(22)*PAR(31))
GO TO (70,80,90) K
70 AUX=QL1+QS1+QCLT
RETURN
80 AUX=QL2+QS2+QKCH
RETURN
90 AUX=QL3+QS3+QDEL-QKCH
RETURN
END

```

APPENDIX 6

COMPUTER PROGRAM TO CALCULATE THE EFFECT OF
VACUUM LOSS OF THE PERFORMANCE OF THE
FIRST CONFIGURATION WITH ONE GLASS COVER

The outputs of this computer program are:

- a) Glass temperature
- b) Receiver temperature
- c) Inlet water temperature
- d) Outlet water temperature
- e) Thermal efficiency

```

DIMENSION X(2),WA(8),PAR(28)
EXTERNAL AUX
DOUBLE PRECISION AUX,X,WA,PAR,EPS
READ*, TSL1,TDL1,RSL1,RDL1,ABL1,ABL2,REL2,TRS1,
1RES1,ABS1,RES2,ABS2
READ*, AL,DIV,D1,D2,DI2,TFIN,RM,SR,TAIR,APER,
1WFR,VAIR,FINT,PS
READ*, X(1),X(2)
EPS=1.0D-6
NSIG=5
N=2
ITMAX=500
PAR(1)=TSL1
PAR(2)=TDL1
PAR(3)=RSL1
PAR(4)=RDL1
PAR(5)=ABL1
PAR(6)=ABL2
PAR(7)=REL2
PAR(8)=TRS1
PAR(9)=RES1
PAR(10)=ABS1
PAR(11)=RES2
PAR(12)=ABS2
PAR(13)=AL
PAR(14)=DIV
PAR(15)=D1
PAR(16)=D2
PAR(17)=DI2
PAR(18)=TFIN
PAR(19)=RM
PAR(20)=SR
PAR(21)=TAIR
PAR(22)=APER
PAR(23)=WFR
PAR(24)=VAIR
PAR(25)=FINT
PAR(26)=0
PAR(27)=0
PAR(28)=PS
I=1
40 CONTINUE
CALL ZSYSTM(AUX,EPS,NSIG,N,X,ITMAX,WA,PAR,IER)
ITMAX=500
PRINT*, '*****'
PRINT '(/T10,A,I2)', 'STEP=',I
PRINT '(/T10,A,F10.5)', 'GLASS TEMP=',X(1)
PRINT '(/T10,A,F10.5)', 'RECEIVER TEMP=',X(2)
PRINT '(/T10,A,F10.5)', 'WATER TEMP. IN=',PAR(18)
PRINT '(/T10,A,F10.5)', 'WATER TEMP. OUT=',PAR(26)
PRINT '(/T10,A,F6.4)', 'THERMAL EFFICIENCY=',PAR(27)
I=I+1
KA=(AL/DIV)+1.
IF(I.EQ.KA) GO TO 70
PAR(18)=PAR(26)
GO TO 40
70 CONTINUE
STOP

```

```

END
FUNCTION AUX(X,K,PAR)
DIMENSION X(2),PAR(28)
DOUBLE PRECISION AUX,X,PAR
PI=3.14159
A1=PI*PAR(15)*PAR(14)
A2=PI*PAR(16)*PAR(14)
RSKY=5.26338E-13*PAR(21)**6.0
EB1=5.669E-8*X(1)**4.0
EB2=5.669E-8*X(2)**4.0
R1=1.0/(A2*PAR(1))
R2=1.0/(A2*PAR(2))
REQ=R1*R2/(R1+R2)
R3=1.0/(A1*(1.0-PAR(1)-PAR(2)-PAR(3)))
R4=PAR(4)/(A1*PAR(5)*(1.0-PAR(1)-PAR(2)-PAR(3)))
R5=R4
R6=1.0/(A2*(1.0-PAR(1)-PAR(2)-PAR(3)))
R7=(1.0-PAR(6))/(A2*PAR(6))
B=(RSKY*R4+EB1*R3)/(R4+R3)
E=(RSKY/REQ+EB2/R7+EB1/(R5+R6))/(1.0/REQ+1.0/R6+
11.0/R7-R5/(R6*(R5+R6)))
D=(EB1*R6+E*R5)/(R5+R6)
QL1=(B-EB1)/R4+(D-EB1)/R5
QL2=(E-EB2)/R7
RS1=1.0/PAR(8)
RS2=1.0/(1.0-PAR(8))
RS3=PAR(9)/(PAR(10)*(1.0-PAR(8)))
RS4=RS3
RS5=RS2
RS6=PAR(11)/PAR(12)
SRI=PAR(20)*PAR(19)*PAR(25)*PAR(14)*((PAR(22)-
1PAR(15))+(PAR(15)-PAR(16))*PAR(8)**2)+PAR(20)*PAR(
214)*PAR(16)
BS=(SRI*RS3)/(RS2+RS3)
ES=(SRI/RS1)/(1.0/RS1+1.0/RS5+1.0/RS6-RS4/(
1RS5*(RS4+RS5)))
DS=(ES*RS4)/(RS4+RS5)
QS1=(BS+DS)/RS3
QS2=ES/RS6
TKALT=2.59E-2
VALT=15.06E-6
RELT=0.2778*PAR(24)*PAR(15)/VALT
IF(RELT.LT.1000.0) GO TO 20
IF(RELT.GT.1000.0) GO TO 30
20 SULT=0.4+0.54*RELT**0.52
GO TO 35
30 SULT=0.3*RELT**0.6
35 CONTINUE
QCLT=A1*TKALT*SULT*(PAR(21)-X(1))/PAR(15)
IF(PAR(18).LT.373) GO TO 36
IF(PAR(18).GT.373) GO TO 37
36 DVIW=3.361E-9*EXP(1640/PAR(18))
DHIW=1.88E-6*EXP(1872/PAR(18))
GO TO 38
37 DVIW=1.532E-8*EXP(1103/PAR(18))
DHIW=8.84E-6*EXP(1288/PAR(18))
38 CONTINUE
TKW=66.8E-2
PRW=2.55
CPW=4000

```



```

IF(X(2).LT.373) GO TO 41
IF(X(2).GT.373) GO TO 42
41 DMIWL=1.88E-6*EXP(1872/X(2))
GO TO 43
42 DMIWL=8.84E-6*EXP(1288/X(2))
43 CONTINUE
REW=4.0*PAR(23)/(PI*PAR(17)*3600.0*DVIW)
IF(REW.LT.2100) GO TO 44
IF(REW.LT.5000) GO TO 45
IF(REW.GT.5000) GO TO 46
44 SU=(48.0/11.0)+(0.0668*(PAR(17)/PAR(14))*REW*PRW)
1/(1.0+0.04*((PAR(17)/PAR(14))*REW*PRW)**0.67)
GO TO 47
45 SU=0.166*(REW**0.67-125)*PRW**0.33*(1.0+
1*(PAR(17)/PAR(14))*0.67)*(DMIW/DMIWL)**0.14
GO TO 47
46 FR=(1.82*LOG10(REW)-1.64)**(-2)
SU=((FR/8.0)*REW*PRW)/((1.07+12.7*((FR/8.0)**0.5))*
1*(PRW**0.67-1.0))
47 CONTINUE
HTC=SU*TKW/PAR(17)
AP=3.6*HTC*PI*PAR(17)/(PAR(23)*CPW)
PAR(26)=PAR(18)*EXP(-AP*PAR(14))+X(2)*(1.0-
1*EXP(-AP*PAR(14)))
PAR(27)=(PAR(26)-PAR(18))*PAR(23)*CPW/(3.6*PAR(20)
1*PAR(14)*PAR(22))
FMT=X(2)+(PAR(18)-X(2))*(1.0-EXP(-AP*PAR(14)))/
1*(AP*PAR(14))
QDEL=HTC*PI*PAR(17)*PAR(14)*(FMT-X(2))
AT=200.0/(X(1)+X(2))
GRPR=2737*((1.0+2.0*AT)**2.0)*(AT**4.0)*ABS(X(2)-
1X(1))*((50.0*(PAR(15)-PAR(16))**3.0)*PAR(28)**2.0
1THKA=0.002528*((X(2)+X(1))/2.0)**1.5/((X(2)+X(1))/
12.0+200.0)
IF(GRPR.LT.1000) GO TO 48
ECK=0.18*(GRPR)**0.25
QCC=PAR(14)*THKA*ECK*(A1+A2)*(X(2)-X(1))/(PAR(15)-PAR(16))
GO TO 49
48 FMP=552.11E-12*((X(2)+X(1))/2.0)**2.0/((X(2)+X(1))*
10.9+198.6)*PAR(28))
QCC=PAR(14)*THKA*((A1+A2)/2.0)*(X(2)-X(1))/(PAR(15)-
1PAR(16))/2.0+2.0*FMP)
49 CONTINUE
GO TO (50,60) K
50 AUX=QL2+QS2+QDEL-QCC
RETURN
60 AUX=QL1+QS1+QCLT+QCC
RETURN
END

```

APPENDIX 7

COMPUTER PROGRAM TO CALCULATE THE PERFORMANCE
OF THE ABSORBER OF THE SECOND CONFIGURATION
WITH ONE GLASS COVER

The outputs of this computer program are:

- a) Glass temperature
- b) Inlet black liquid temperature
- c) Outlet black liquid temperature
- d) Thermal efficiency

```

DIMENSION X(1),WA(3),PAR(25)
EXTERNAL AUX
DOUBLE PRECISION AUX,X,WA,PAR,EPS
READ*, TSL1,TDL1,RSL1,RDL1,ABL1,ABL2,REL2,TRS1,
1RES1,ABS1,RES2,ABS2
READ*, AL,DIV,D1 ,DI1,TFIN,RH,SR,TAIR,APER,
1WFR,VAIR,FINT
READ*, X(1)
EPS=1.0D-6
NSIG=5
N=1
ITMAX=200
PAR(1)=TSL1
PAR(2)=TDL1
PAR(3)=RSL1
PAR(4)=RDL1
PAR(5)=ABL1
PAR(6)=ABL2
PAR(7)=REL2
PAR(8)=TRS1
PAR(9)=RES1
PAR(10)=ABS1
PAR(11)=RES2
PAR(12)=ABS2
PAR(13)=AL
PAR(14)=DIV
PAR(15)=D1
PAR(16)=0
PAR(17)=DI1
PAR(18)=TFIN
PAR(19)=RH
PAR(20)=SR
PAR(21)=TAIR
PAR(22)=APER
PAR(23)=WFR
PAR(24)=VAIR
PAR(25)=FINT
I=1
40 CONTINUE
CALL ZSYSTH(AUX,EPS,NSIG,N,X,ITMAX,WA,PAR,IER)
ITMAX=200
CPW1=4187
EFF=(PAR(16)-TFIN)*WFR*CPW1/(3.6*SR*DIV*APER)
PRINT*, '*****'
PRINT '(/T10,A,I2)', 'STEP=', I
PRINT '(/T10,A,F10.5)', 'GLASS TEMP=', X(1)
PRINT '(/T10,A,F10.5)', 'BLACK LIQ. TEMP. IN=', TFIN
PRINT '(/T10,A,F10.5)', 'BLACK LIQ. TEMP. OUT=', PAR(16)
PRINT '(/T10,A,F6.4)', 'THERMAL EFFICIENCY=', EFF
I=I+1
KA=(AL/DIV)+1.
IF(I.EQ.KA) GO TO 70
TFIN=PAR(16)
PAR(18)=PAR(16)
GO TO 40
70 CONTINUE
STOP
END

```

```

FUNCTION AUX(X,K,PAR)
DIMENSION X(1),PAR(25)
DOUBLE PRECISION AUX,X,PAR
PI=3.14159
A1=PI*PAR(15)*PAR(14)
A2=PI*PAR(17)*PAR(14)
RSKY=5.24338E-13*PAR(21)**6.0
EB1=5.669E-8*X(1)**4.0
EB2=5.669E-8*PAR(18)**4.0
R1=1.0/(A2*PAR(1))
R2=1.0/(A2*PAR(2))
REQ=R1*R2/(R1+R2)
R3=1.0/(A1*(1.0-PAR(1)-PAR(2)-PAR(3)))
R4=PAR(4)/(A1*PAR(5)*(1.0-PAR(1)-PAR(2)-PAR(3)))
R5=R4
R6=1.0/(A2*(1.0-PAR(1)-PAR(2)-PAR(3)))
R7=(1.0-PAR(6))/(A2*PAR(6))
B=(RSKY*REQ+EB1*R3)/(R4+R3)
E=(RSKY/REQ+EB2/R7+EB1/(R5+R6))/(1.0/REQ+1.0/R6+
1.0/R7-R5/(R6*(R5+R6)))
D=(EB1*R6+E*R5)/(R5+R6)
QL1=(B-EB1)/R4+(D-EB1)/R5
QL2=(E-EB2)/R7
RS1=1.0/PAR(8)
RS2=1.0/(1.0-PAR(8))
RS3=PAR(9)/(PAR(10)*(1.0-PAR(8)))
RS4=RS3
RS5=RS2
RS6=PAR(11)/PAR(12)
SRI=PAR(20)*PAR(19)*PAR(25)*PAR(14)*(PAR(22)-
3*PAR(15))+PAR(20)*PAR(14)*PAR(17)
BS=(SRI*RS3)/(RS2+RS3)
ES=(SRI/RS1)/(1.0/RS1+1.0/RS5+1.0/RS6-RS4/(
1*RS5*(RS4+RS5)))
DS=(ES*RS4)/(RS4+RS5)
QS1=(BS+DS)/RS3
QS2=ES/RS6
TKALT=2.59E-2
VALT=15.06E-6
RELT=0.2778*PAR(24)*PAR(15)/VALT
IF(RELT.LT.1000.0) GO TO 20
IF(RELT.GT.1000.0) GO TO 30
20 SULT=0.4+0.54*RELT**0.52
GO TO 35
30 SULT=0.3*RELT**0.6
35 CONTINUE
QCLT=A1*TKALT*SULT*(PAR(21)-X(1))/PAR(15)
IF(PAR(18).LT.373) GO TO 36
IF(PAR(18).GT.373) GO TO 37
36 DVIW=3.361E-9*EXP(1660/PAR(18))
DNIW=1.88E-6*EXP(1872/PAR(18))
GO TO 38
37 DVIW=1.532E-8*EXP(1103/PAR(18))
DNIW=8.84E-6*EXP(1288/PAR(18))
38 CONTINUE
TKW=44.8E-2
PRW=2.55
CPW=4000.
IF(X(1).LT.373) GO TO 41
IF(X(1).GT.373) GO TO 42

```

```

41 DMIWL=1.88E-6*EXP(1872/X(1))
   GO TO 43
42 DMIWL=8.84-6*EXP(1288/X(1))
43 CONTINUE
   REW=4.0*PAR(23)/(PI*PAR(17)*3600.0*DUIW)
   IF(REW.LT.2100) GO TO 44
   IF(REW.LT.5000) GO TO 45
   IF(REW.GT.5000) GO TO 46
44 SU=(48.0/11.0)+(0.0668*(PAR(17)/PAR(14))*REW*PRW)
   1/((1.0+0.04*((PAR(17)/PAR(14))*REW*PRW)**0.67)
   GO TO 47
45 SU=0.166*(REW**0.67-125)*PRW**0.33*(1.0+(PAR(17)/
   1*PAR(14))**0.67)*ABS(DMIW/DMIWL)**0.14
   GO TO 47
46 FR=(1.82*LOG10(REW)-1.64)**(-2)
   SU=((FR/8.0)*REW*PRW)/((1.07+12.7*((FR/8.0)**0.5))*
   1*(PRW**0.67-1.0))
47 CONTINUE
   HTC=SU*TKW/PAR(17)
   TFOUT=(PAR(23)*CPW*PAR(18)/3.6-0.5*HTC*PI*PAR(17)
   1*PAR(14)*(PAR(18)-2.0*X(1))+QL2+QS2)/(PAR(23)*
   3*CPW/3.6+0.5*HTC*PI*PAR(17)*PAR(14))
   PAR(16)=TFOUT
   FMT=0.5*(PAR(18)+TFOUT)
   QDEL=HTC*PI*PAR(17)*PAR(14)*(FMT-X(1))
   AUX=QL1+QS1+QCLT+QDEL
   RETURN
   END

```

APPENDIX 8

COMPUTER PROGRAM TO CALCULATE THE PERFORMANCE
OF THE ABSORBER OF THE SECOND CONFIGURATION
WITH TWO GLASS COVERS

The outputs of this computer program are:

- a) Outer glass temperature
- b) Inner glass temperature
- c) Inlet black liquid temperature
- d) Outlet black liquid temperature
- e) Thermal efficiency

```

DIMENSION X(2),WA(8),PAR(34)
EXTERNAL AUX
DOUBLE PRECISION AUX,X,WA,PAR,EPS
READ*,TSL1,TSL2,TDL1,TDL2,RSL1,RSL2,RDL1,RDL2,
1ABL1,ABL2,ABL3,REL3,TRS1,TRS2,RES1,RES2,ABS1,
2ABS2,RES3,ABS3
READ*,AL,DIU,D1,D2, DI2,TFIN,RM,SR,TAIR,APER,
1WFR,VAIR,FINT
READ*, X(1),X(2)
EPS=1.0D-2
NSIG=2
N=2
ITMAX=300
PAR(1)=TSL1
PAR(2)=TSL2
PAR(3)=TDL1
PAR(4)=TDL2
PAR(5)=RSL1
PAR(6)=RSL2
PAR(7)=RDL1
PAR(8)=RDL2
PAR(9)=ABL1
PAR(10)=ABL2
PAR(11)=ABL3
PAR(12)=REL3
PAR(13)=TRS1
PAR(14)=TRS2
PAR(15)=RES1
PAR(16)=RES2
PAR(17)=ABS1
PAR(18)=ABS2
PAR(19)=RES3
PAR(20)=ABS3
PAR(21)=AL
PAR(22)=DIU
PAR(23)=D1
PAR(24)=D2
PAR(25)=0
PAR(26)=DI2
PAR(27)=TFIN
PAR(28)=RM
PAR(29)=SR
PAR(30)=TAIR
PAR(31)=APER
PAR(32)=WFR
PAR(33)=VAIR
PAR(34)=FINT
I=1
40 CONTINUE
ITMAX=300
CALL ZSYSTEM(AUX,EPS,NSIG,N,X,ITMAX,WA,PAR,IER)
CPW1=4187
EFF=(PAR(25)-TFIN)*WFR*CPW1/(3.6*SR*DIU*APER)
PRINT,'*****'
PRINT '(//T10,A,I2)', 'STEP=',I
PRINT '(//T10,A,F10.5)', 'OUTER GLASS TEMP.=',X(1)
PRINT '(//T10,A,F10.5)', 'INNER GLASS TEMP.=',X(2)
PRINT '(//T10,A,F10.5)', 'BLACK LIQ. TEMP. IN=',TFIN

```

```

PRINT '(/T10,A,F10.5)', 'BLACK LIQ. TEMP. OUT=', PAR(25)
PRINT '(/T10,A,F6.4)', 'THERMAL EFFICIENCY=', EFF
I=I+1
KA=(AL/DIV)+1
IF(I.EQ.KA) GO TO 70
TFIN=PAR(25)
PAR(27)=PAR(25)
GO TO 40
70 CONTINUE
STOP
END
FUNCTION AUX(X,K,PAR)
DIMENSION X(2), PAR(34)
DOUBLE PRECISION AUX,X,PAR
PI=3.14159
A1=PI*PAR(23)*PAR(22)
A2=PI*PAR(24)*PAR(22)
A3=PI*PAR(26)*PAR(22)
RSKY=5.26338E-13*PAR(30)**6.0
EB1=5.669E-8*X(1)**4.0
EB2=5.669E-8*X(2)**4.0
EB3=5.669E-8*PAR(27)**4.0
R1=1.0/(A3*PAR(1)*PAR(2))
R2=1.0/(A3*PAR(3)*PAR(4))
REQ3=R1*R2/(R1+R2)
HE1=1.0-PAR(1)-PAR(3)-PAR(5)
HE2=1.0-PAR(2)-PAR(4)-PAR(6)
R3=1.0/(A1*HE1)
R4=PAR(7)/(A1*PAR(9)*HE1)
R5=1.0/(A2*HE1*HE2)
R6=PAR(8)/(A2*PAR(10)*HE2)
R7=1.0/(A3*HE2)
R8=1.0/(A2*PAR(1)*HE2)
R9=1.0/(A2*PAR(3)*HE2)
REQ1=R8*R9/(R8+R9)
R10=1.0/(A3*PAR(4)*HE1)
R11=1.0/(A3*PAR(2)*HE1)
REQ2=R10*R11/(R10+R11)
R12=(1.0-PAR(11))/(A3*PAR(11))
Z3=1.0/REQ3+1.0/REQ2+1.0/(R6+R7)+1.0/R12
Z5=RSKY/REQ3+EB2/(R6+R7)+EB3/R12
Z1=EB2/R6+RSKY/REQ1
Z2=1.0/R5+1.0/R6+1.0/REQ1
Z4=1.0/R4+1.0/R5-1.0/(Z3*RS**2)+(Z6*REQ2-1.0)
Z6=Z5*REQ2**2
Z1=EB1/R4+Z4/(Z3*RS)+Z5/(Z6*REQ2)
P=(EB1*R3+RSKY*R4)/(R3+R4)
D=Z1/Z2
H=(Z2*Z5*REQ2+Z1)/(Z2*Z6*REQ2)
E=(Z1+Z2*Z4*RS)/(Z2*Z3*RS)
G=(EB2*R7+H*R6)/(R6+R7)
QL1=(B-EB1)/R4+(D-EB1)/R4
QL2=(E-EB2)/R6+(G-EB2)/R6
QL3=(H-EB3)/R12
RS1=1.0/(PAR(13)*PAR(14))
RS2=1.0/(1.0-PAR(13))
RS3=PAR(15)/(PAR(17)*(1.0-PAR(13)))
RS4=1.0/((1.0-PAR(13))*(1.0-PAR(14)))
RS5=PAR(16)/(PAR(18)*(1.0-PAR(14)))
RS6=1.0/(1.0-PAR(14))

```



```

RS7=1.0/(PAR(13)*(1.0-PAR(14)))
RS8=1.0/(PAR(14)*(1.0-PAR(13)))
RS9=PAR(19)/PAR(20)
SRI=PAR(29)*PAR(28)*PAR(34)*PAR(22)*((PAR(31)-
1*PAR(23))+PAR(23)-PAR(24))*PAR(13)**2.0)
2*PAR(29)*PAR(22)*PAR(24)
ZS6=1.0/RS1+1.0/RS8+1.0/(RS5+RS6)+1.0/RS9
ZS5=SRI/RS1
ZS4=SRI/RS7
ZS3=1.0/RS4+1.0/RS5+1.0/RS7
ZS2=1.0/RS3+1.0/RS4-1.0/(ZS3*RS4**2.0)+(ZS6*RS8-
11.0)/(ZS6*RS8**2.0)
ZS1=ZS4/(ZS3*RS4)+ZS5/(ZS6*RS8)
BS=SRI*RS3/(RS2+RS3)
US=ZS1/ZS2
HS=(ZS2*ZS5*RS8+ZS1)/(ZS2*ZS6*RS8)
ES=(ZS2*ZS4*RS4+ZS1)/(ZS2*ZS3*RS4)
GS=HS*RS5/(RS5+RS6)
QS1=(BS+US)/RS3
QS2=(ES+GS)/RS5
QS3=HS/RS9
TKALT=2.59E-2
VALT=15.06E-6
RELT=0.2778*PAR(33)*PAR(23)/VALT
IF(RELT.LT.1000.0) GO TO 20
IF(RELT.GT.1000.0) GO TO 30
20 SULT=0.4+0.54*RELT**0.52
GO TO 35
30 SULT=0.3*RELT**0.6
35 CONTINUE
QCLT=A1*TKALT*SULT*(PAR(30)-X(1))/PAR(23)
TKW=66.8E-2
IF(PAR(27).LT.373) GO TO 36
IF(PAR(27).GT.373) GO TO 37
36 DVIW=3.361E-9*EXP(1660/PAR(27))
DMIW=1.88E-6*EXP(1872/PAR(27))
GO TO 38
37 DVIW=1.532E-8*EXP(1103/PAR(27))
DMIW=8.84E-6*EXP(1288/PAR(27))
38 CONTINUE
PRW=2.55
CPW=4000
IF(X(2).LT.353) GO TO 41
IF(X(2).GT.353) GO TO 42
41 DMIWL=1.88E-6*EXP(1872/X(2))
GO TO 43
42 DMIWL=8.84E-6*EXP(1288/X(2))
43 CONTINUE
REW=4.0*PAR(32)/(PI*PAR(26)*3600.0*DVIW)
IF(REW.LT.2100) GO TO 44
IF(REW.LT.5000) GO TO 45
IF(REW.GT.5000) GO TO 46
44 SU=(48.0/11.0)+(0.0668*(PAR(26)/PAR(22))*REW*PRW)/
1*(1.0+0.04*((PAR(26)/PAR(22))*REW*PRW)**0.67)
GO TO 47
45 SU=0.166*(REW**0.67-125)*PRW**0.33*(1.0+(PAR(26)
1/PAR(22))**0.67)*(DMIW/DMIWL)**0.14
GO TO 47
46 FR=(1.82*LOG10(REW)-1.64)**(-2)
SU=((FR/8.0)*REW*PRW)/((1.07+12.7*((FR/8.0)**0.5))
1*(PRW**0.67-1.0))
47 CONTINUE
HTC=SU*TKW/PAR(26)
TFOUT=(PAR(32)*CPW*PAR(27)/3.6-0.5*HTC*PI*PAR(26)
4*PAR(22)*(PAR(27)-2.0*X(2))+QL3+QS3)/(PAR(32)*CPW/
23.6+0.5*HTC*PI*PAR(26)*PAR(22))
PAR(25)=TFOUT
FHT=0.5*(PAR(27)+TFOUT)
QDEL=HTC*PI*PAR(26)*PAR(22)*(FHT-X(2))
GO TO (70,80) K
70 AUX=QL1+QS1+QCLT
RETURN
80 AUX=QL2+QS2+QDEL
RETURN
END

```

APPENDIX 9

COMPUTER PROGRAM TO CALCULATE THE PERFORMANCE
OF THE ABSORBER OF THE THIRD CONFIGURATION

The outputs of this computer program are:

- a) Outer glass temperature
- b) Inner glass temperature
- c) Receiver temperature
- d) Inlet air temperature
- e) Outlet air temperature
- e) Final pressure
- f) Thermal efficiency

```

DIMENSION X(3),WA(14),PAR(38)
EXTERNAL AUX
DOUBLE PRECISION AUX,X,WA,PAR,EPS
READ*,TSL1,TSL2,TDL1,TDL2,RSL1,RSL2,RDL1,RDL2,
1ABL1,ABL2,ABL3,REL3,TRS1,TRS2,RES1,RES2,ABS1,
2ABS2,RES3,ABS3
READ*,AL,DIV,D1,D2,DI2,DP,TFIN,RH,SR,TAIR,APER,
1U0,VAIR,FINT,PR
READ*,X(1),X(2),X(3)
EPS=1.0D-2
NSIG=2
N=3
ITMAX=300
EV=0.423*(DP/DI2)+0.328
PAR(1)=TSL1
PAR(2)=TSL2
PAR(3)=TDL1
PAR(4)=TDL2
PAR(5)=RSL1
PAR(6)=RSL2
PAR(7)=RDL1
PAR(8)=RDL2
PAR(9)=ABL1
PAR(10)=ABL2
PAR(11)=ABL3
PAR(12)=REL3
PAR(13)=TRS1
PAR(14)=TRS2
PAR(15)=RES1
PAR(16)=RES2
PAR(17)=ABS1
PAR(18)=ABS2
PAR(19)=RES3
PAR(20)=ABS3
PAR(21)=AL
PAR(22)=DIV
PAR(23)=D1
PAR(24)=D2
PAR(25)=DI2
PAR(26)=DP
PAR(27)=TFIN
PAR(28)=RH
PAR(29)=SR
PAR(30)=TAIR
PAR(31)=APER
PAR(32)=U0
PAR(33)=VAIR
PAR(34)=FINT
PAR(35)=EV
PAR(36)=0
PAR(37)=0
PAR(38)=PR
I=1
40 CONTINUE
ITMAX=300
CALL ZSYSTM(AUX,EPS,NSIG,N,X,ITMAX,WA,PAR,IER)
US=5.5723E-5*EXP(-360.37/PAR(27))
DEN=(1.293/(1.+0.00367*(PAR(27)-273)))*PAR(38)

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```

G1=U0*DEN
DPR=((150.*(1.-EV)*VS/(DP*G1)+1.75)*((1.-EV)/(EV**3.
2))*((DIU/DP)*(G1**2./DEN))/101325
PAR(38)=PAR(38)-DPR
PRINT*, '*****'
PRINT '(//T10,A,I2)', 'STEP=', I
PRINT '(//T10,A,F10.5)', 'OUTER GLASS TEMP.=', X(1)
PRINT '(//T10,A,F10.5)', 'INNER GLASS TEMP.=', X(2)
PRINT '(//T10,A,F10.5)', 'RECEIVER TEMP.=', X(3)
PRINT '(//T10,A,F10.5)', 'AIR TEMP. IN=', PAR(27)
PRINT '(//T10,A,F10.5)', 'AIR TEMP. OUT=', PAR(36)
PRINT '(//T10,A,F6.4)', 'FINAL PRESSURE=', PAR(38)
PRINT '(//T10,A,F6.4)', 'THERMAL EFFICIENCY=', PAR(37)
I=I+1
KA=(AL/DIU)+1
IF(I.EQ.KA) GO TO 70
PAR(27)=PAR(36)
GO TO 40
70 CONTINUE
STOP
END
FUNCTION AUX(X,K,PAR)
DIMENSION X(3), PAR(38)
DOUBLE PRECISION AUX,X,PAR
PI=3.14159
A1=PI*PAR(23)*PAR(22)
A2=PI*PAR(24)*PAR(22)
A3=PI*PAR(25)*PAR(22)
RSKY=5.26338E-13*PAR(30)**6.0
EB1=5.669E-8*X(1)**4.0
EB2=5.669E-8*X(2)**4.0
EB3=5.669E-8*X(3)**4.0
R1=1.0/(A3*PAR(1)*PAR(2))
R2=1.0/(A3*PAR(3)*PAR(4))
REQ3=R1*R2/(R1+R2)
HE1=1.0-PAR(1)-PAR(3)-PAR(5)
HE2=1.0-PAR(2)-PAR(4)-PAR(6)
R3=1.0/(A1*HE1)
R4=PAR(7)/(A1*PAR(9)*HE1)
R5=1.0/(A2*HE1*HE2)
R6=PAR(8)/(A2*PAR(10)*HE2)
R7=1.0/(A3*HE2)
R8=1.0/(A2*PAR(1)*HE2)
R9=1.0/(A2*PAR(3)*HE2)
REQ1=R8*R9/(R8+R9)
R10=1.0/(A3*PAR(4)*HE1)
R11=1.0/(A3*PAR(2)*HE1)
REQ2=R10*R11/(R10+R11)
R12=(1.0-PAR(11))/(A3*PAR(11))
Z6=1.0/REQ3+1.0/REQ2+1.0/(R6+R7)+1.0/R12
Z5=RSKY/REQ3+EB2/(R6+R7)+EB3/R12
Z4=EB2/R6+RSKY/REQ1
Z3=1.0/R5+1.0/R6+1.0/REQ1
Z2=1.0/R4+1.0/R5-1.0/(Z3*R5**2)+(Z6*REQ2-1.0)
1/(Z6*REQ2**2)
Z1=EB1/R4+Z4/(Z3*R5)+Z5/(Z6*REQ2)
B=(EB1*R3+RSKY*R4)/(R3+R4)
D=Z1/Z2
H=(Z2*Z5*REQ2+Z1)/(Z2*Z6*REQ2)
E=(Z1+Z2*Z4*R5)/(Z2*Z3*R5)

```

```

G=(EB2*R7+H*R6)/(R6+R7)
QL1=(B-EB1)/R4+(D-EB1)/R4
QL2=(E-EB2)/R6+(G-EB2)/R6
QL3=(H-EB3)/R12
RS1=1.0/(PAR(13)*PAR(14))
RS2=1.0/(1.0-PAR(13))
RS3=PAR(15)/(PAR(17)*(1.0-PAR(13)))
RS4=1.0/((1.0-PAR(13))*(1.0-PAR(14)))
RS5=PAR(16)/(PAR(18)*(1.0-PAR(14)))
RS6=1.0/(1.0-PAR(14))
RS7=1.0/(PAR(13)*(1.0-PAR(14)))
RS8=1.0/(PAR(14)*(1.0-PAR(13)))
RS9=PAR(19)/PAR(20)
SRI=PAR(29)*PAR(28)*PAR(34)*PAR(22)*((PAR(31)-
1*PAR(23))+PAR(23)-PAR(24))*PAR(13)**2.0)
2*PAR(29)*PAR(22)*PAR(24)
ZS6=1.0/RS1+1.0/RS8+1.0/(RS5+RS6)+1.0/RS9
ZS5=SRI/RS1
ZS4=SRI/RS7
ZS3=1.0/RS4+1.0/RS5+1.0/RS7
ZS2=1.0/RS3+1.0/RS4-1.0/(ZS3*RS4**2.0)+(ZS6*RS8-
11.0)/(ZS6*RS8**2.0)
ZS1=ZS4/(ZS3*RS4)+ZS5/(ZS6*RS8)
BS=SRI*RS3/(RS2+RS3)
DS=ZS1/ZS2
HS=(ZS2*ZS5*RS8+ZS1)/(ZS2*ZS6*RS8)
ES=(ZS2*ZS4*RS4+ZS1)/(ZS2*ZS3*RS4)
GS=HS*RS5/(RS5+RS6)
QS1=(BS+DS)/RS3
QS2=(ES+GS)/RS5
QS3=HS/RS9
TKALT=2.59E-2
VALT=15.06E-6
RELT=0.2778*PAR(33)*PAR(23)/VALT
IF(RELT.LT.1000.0) GO TO 20
IF(RELT.GT.1000.0) GO TO 30
20 SULT=0.4+0.54*RELT**0.52
GO TO 40
30 SULT=0.3*RELT**0.6
40 CONTINUE
QCLT=A1*TKALT*SULT*(PAR(30)-X(1))/PAR(23)
DEAIR=(1.293/(1+0.00367*(PAR(27)-273)))*PAR(38)
TKA=4.27E-2
VBAIR=5.5723E-5*EXP(-360.37/PAR(27))
F=(3.0*(1.0-PAR(35))*PAR(22)*PI*PAR(25)**2.0)/(2.0
1*PAR(26))
GAIR=PAR(32)*DEAIR
VB=0.25*GAIR*PI*PAR(25)**2.0
CPAIR=1000
PR1=0.7
HTC1=(2.0+0.6*PR1**0.33*(PAR(26)*GAIR/VBAIR)**0.5)
1*(TKA/PAR(26))
HTC=17
TFOUT=(CPAIR*VB*PAR(27)+0.5*HTC1*F*(2.0*X(3)-PAR(27))+
10.5*PI*PAR(25)*PAR(22)*HTC*(2.0*X(2)-PAR(27)))/(
2*CPAIR*VB+0.5*HTC1*F+0.5*PI*PAR(25)*PAR(22)*HTC)
QPAIR=0.5*HTC1*F*(2.0*X(3)-PAR(27)-TFOUT)
QAIRS=0.5*PI*PAR(25)*PAR(22)*HTC*(2.0*X(2)-PAR(27)-TFOUT)
PAR(36)=TFOUT
EFF=(TFOUT-PAR(27))*VB*CPAIR/(PAR(29)*PAR(22)*PAR(31))
PAR(37)=EFF
GO TO (70,80,90) K
70 AUX=QL1+QS1+QCLT
RETURN
80 AUX=QL2+QS2-QAIRS
RETURN
90 AUX=QL3+QS3-QPAIR
RETURN
END

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END

3 0 H 0 8 H 8 2 |

FIN