EVACUATED TUBE COLLECTORS

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Contents

1. Introduction

The source of thermal energy required by most distillation processes can range from 70-120°C which can ideally be produced by evacuated tube collectors which can easily achieve this range and have the added advantage of a high performance. With the recent advances in vacuum technology, evacuated tube collectors can be reliably mass-produced. Their high temperature effectiveness is essential to the proper operation of distillation systems.

In the first years of the twentieth century it was recognized that the creation of vacuum between the absorber and the cover of a solar collector would result in a substantial improvement in collector efficiency due to reduction in heat loss through convection and conduction. In 1909, Emmett (1911) proposed several evacuated-tube concepts for solar energy collection, two of which are still sold commercially today. Using a selective absorbing surface in evacuated collectors would also reduce substantially the radiative losses and improve the overall efficiency of the collector. For a survey of evacuated collectors, see Graham (1979). Tubular collectors, with their inherently high compressive strength and resistance to implosion, afford the only practical means for completely eliminating convection and conduction losses by surrounding the receiver with a vacuum on the order of 10^{-4} mm Hg (Fraser 1976; Aranovitch 1981).

The performance of evacuated tube collectors may be improved by introducing a small level of concentration - 1.5 to 2.0 - by forming a mirror from part of the internal concave surface of a glass tube. This reflector can focus radiation on an absorber plate inside the tube. External concentrators of radiation may also be coupled to an evacuated collector for improvement of performance over the simple evacuated tube.

2. Current Designs of Evacuated Tube Collectors

Several commercial firms have developed evacuated tube collectors and the principal features of some of them are described in this section. Some of the types of evacuated tube collectors are shown schematically in Figure 1 which represent cross sections of several glass evacuated-tube collector concepts. The simplest design is basically a small flat-plate collector housed inside an evacuated cylinder Figure 1(A). If the receiver is metal, a glass-to-metal seal is required to maintain a vacuum.

In addition, a thermal short may occur from inlet to outlet tube unless special precautions are taken. Alternatively, an all-glass collector can be made from concentric glass tubes as shown in Figure 1(B). This collector avoids a glass-to-metal seal but has very limited working fluid pressurization capability. Some investigators have proposed the use of a square absorber circumscribed within the circular region shown. An increased concentration effect would result but the pressurability of the absorber is reduced.

Mildly concentrating tubular collectors can be made using the design of Figure 1(C). Either a single flow-through receiver with fins or a double U-tube as shown can be used. Concentration ratios of from $2/\pi$ to 2.0 can be achieved ideally with this design, but a glass-to-metal seal is required.

One of Emmet's designs is shown in Figure 1(D). It consists of an evacuated vacuum bottle, much like an unsilvered, wide-mouth Dewar flask, into which a metal heat exchanger is inserted. The outer surface of the inner glass tube is the absorber. The heat generated is transferred through the inner glass tube to the metal slip-in heat exchanger. Since this heat transfer is through a glass-to-metal interface that has only intermittent point contacts, significant axial temperature gradients can develop, thereby stressing the glass tube. In addition, a large temperature difference can exist between the inner and outer glass tubes. At the collector ends where the two tubes are joined, a large temperature gradient and consequent thermal stress can exist.

Since the convection is related to the Rayleigh number (Kreider 1979; Lior 1990), which is proportional to the square of the absolute pressure, modest reduction in pressure (e.g. to 0.1 atm) effectively eliminates convection. Gas conduction, on the other hand, is independent of pressure and Fourier Law applies. As the pressure is reduced into the free molecular flow region (i.e. $<10^{-4}$ Torr), gas conduction becomes insignificant. Evacuated collectors are generally produced with an initial pressure of 10^{-4}-10^{-3} Torr by a combination of evacuated bake-out and gettering. Because glasses, particularly borosilicate glasses, are not impermeable to gas molecules in the air, helium in the air was reported to build up inside evacuated glass tubes over a long period of time. And since helium is an excellent conductor compared to the heavier gasses, the heat loss may increase substantially above its initial level.

The level of evacuation required for suppression of convection and conduction can be calculated from basic heat transfer theory. For very low pressure, the conduction heat transfer in a narrow gap is given by

$$q_k = \frac{k\Delta T}{g + 2p} \qquad (1)$$

where g is the gap width and p is the mean free path. For air, the mean free path at atmospheric pressure is about 70 μm. If 99 per cent of the air is removed from a tubular collector, the mean free path increases to 7 mm and conduction heat transfer is affected very little. However, if the pressure is reduced to 10^{-3} Torr the mean free path is 7 cm, which is substantially greater than the heat transfer path length, and conduction heat transfer is effectively suppressed. The relative reduction in heat transfer as a function of mean free path can be derived from the equation:

$$\frac{q_{vac}}{q_k} = \frac{1}{1 + 2p/g} \qquad (2)$$

where Q_k is the conduction heat transfer if convection is suppressed and Q_{vac} is the conduction heat transfer under vacuum. Achieving a vacuum level of 10^{-3}-10^{-4} Torr for a reasonably long period of time is within the grasp of modern vacuum technology. Many of the evacuated collectors sold today use some kind of reflector enhancement. The choice of the reflector depends on the shape of the absorber.

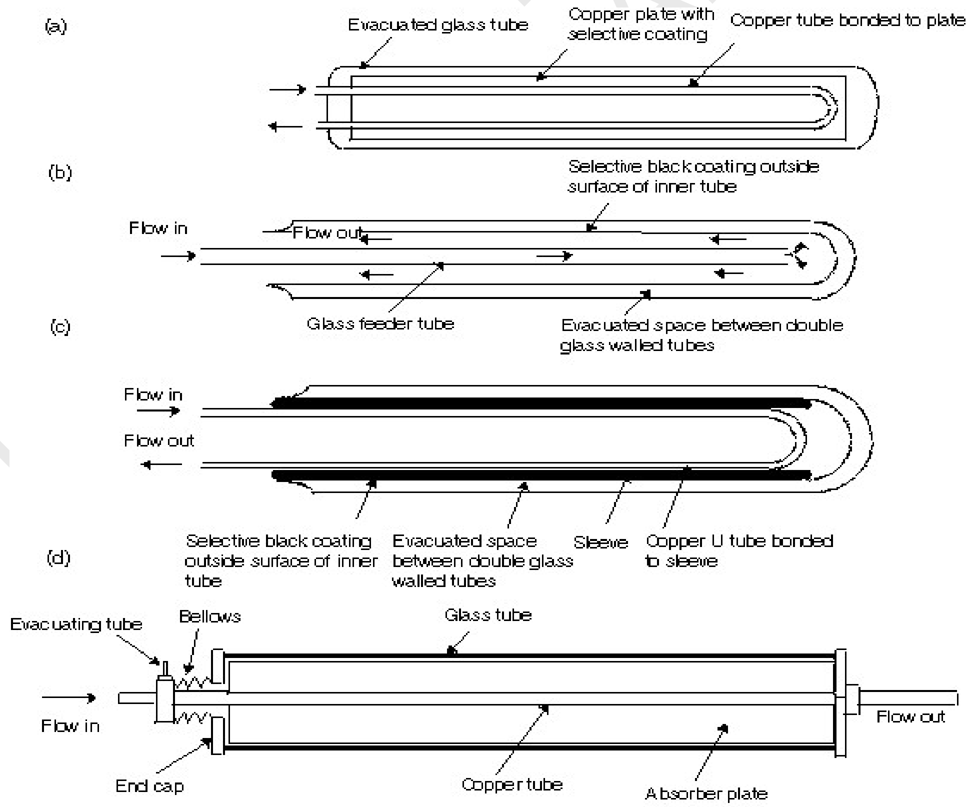


Figure 1. Types of evacuated tube collectors (from Dickinson and Cheremisinoff 1980).

Figure 3. shows several reflector arrangements that have been used with tubular absorbers. The diffuse reflector in Figure 3.a is just a plain white surface behind the tubes. It has the lowest cost and the lowest performance since much of the reflected radiation misses the tubes. The V-groove and circular cylindrical reflectors, shown in Figure 3.b and c, are easy to fabricate. The V-trough reflectors are well matched to flat absorbers, but with tubular absorbers they do not utilize the back of the tubes very well.

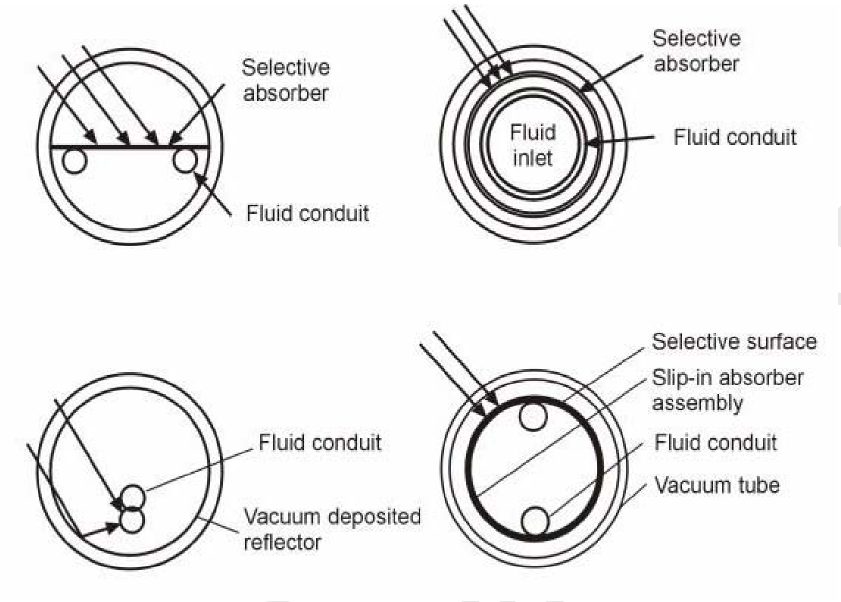


Figure 2. Cross section of four evacuated-tube collectors: (a) flat plate, (b) concentric tube, (c) concentrating, (d) vacuum bottle with slip-in heat exchanger contacting rear surface of receiver.

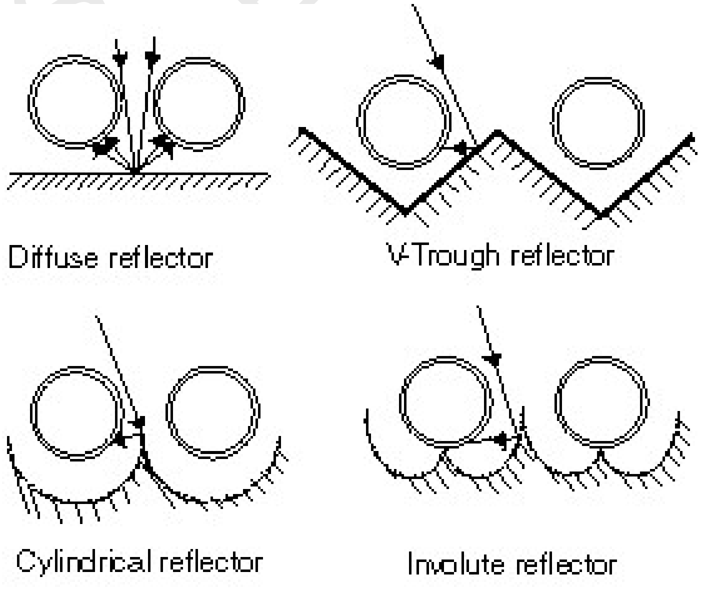


Figure 3. Different reflector configurations used with tubular collectors.

3. Thermal Analysis

Thermal analysis of most evacuated tube collectors can be carried out under steady state condition using the well known Hottel-Whiller-Bliss equation (Duffie and Beckman 1980).

4. Analysis of Flat Plate Evacuated Tube Collector

The flat plate evacuated tube collector consists of multiples of evacuated glass tubes in which one or two axial fluid conduits are located axially and attached to a selective absorber plate. The simplest design is that which contains one circular fluid conduit. A cross section of a single evacuated tube with absorber plate is shown in Figure 4

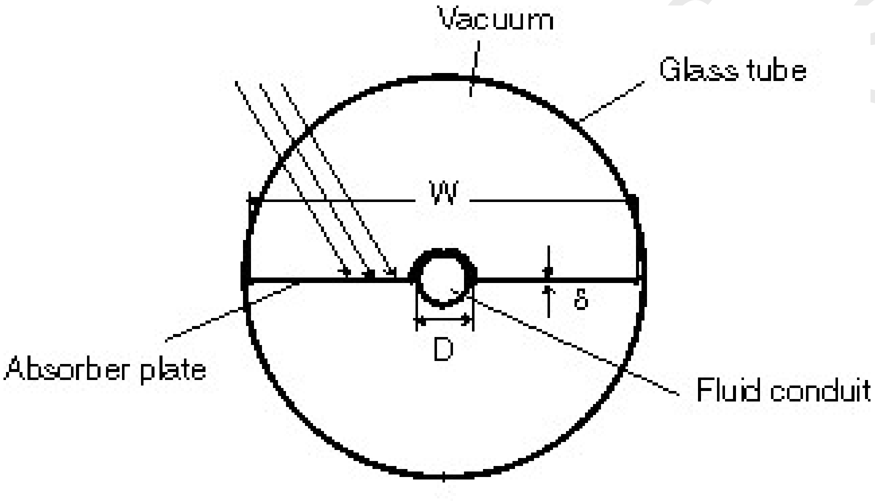


Figure 4. Evacuated tube flat plate collector.

To model the situation shown in Figure 4 the following simplifying assumptions are made:

1. A steady state situation exists.
2. The absorber plate is made of a good conducting sheet of small thickness and the temperature gradient along the axial direction is much smaller than in the radial direction.
3. Properties are independent of temperature.
4. Shading of the absorber plate is negligible.
5. Temperature gradients in the absorber plate in the radial direction at the ends of the absorber plate are negligible.
6. Dust and dirt on the glass tube is negligible.

Following the analysis of Duffie and Beckman (1980), the useful energy gain of most flat plate collectors can be expressed by the equation

$$Q_u = A_c F_R [S - U_L (T_i - T_a)] \qquad (3)$$

where A_c is the collector area, F_R is the collector heat removal factor, S is the solar radiation on the absorber plate, U_L is the collector overall loss coefficient, T_i is the inlet temperature of the collector fluid and T_a is the ambient temperature. F_R is defined as the quantity that relates the actual useful energy gain of a collector to the useful gain if the whole collector surface were at the fluid inlet temperature. It is calculated by Duffie and Beckman (1980) by the following equation:

$$F_R = \frac{\dot{m}C_p}{A_c U_L}\left[1 - e^{-(A_c U_L F'/\dot{m}C_p)}\right] \tag{4}$$

where

$\dot{m}$ is the mass flow rate through the fluid conduit, C_p is the specific heat and F' is the collector efficiency given by the following equation:

$$F' = \frac{\dfrac{1}{U_L}}{W\left\{\dfrac{1}{U_L[D+(W-D)F]} + \dfrac{1}{Cb} + \dfrac{1}{\pi D_i h_{f,i}}\right\}} \tag{5}$$

where D and D_I are, respectively, the outside and inside diameters of the fluid conduit, W is the width of the absorber plate, C_b is the bond conductance between the conduit and the absorber plate, $h_{f,I}$ is the heat transfer coefficient between the fluid and the tube wall and F is the fin efficiency given by:

$$F = \frac{[\tanh\ m(W-D)/2]}{m(W-D)/2} \tag{6}$$

where m is defined as

$$m = \sqrt{U_L / k\delta} \tag{7}$$

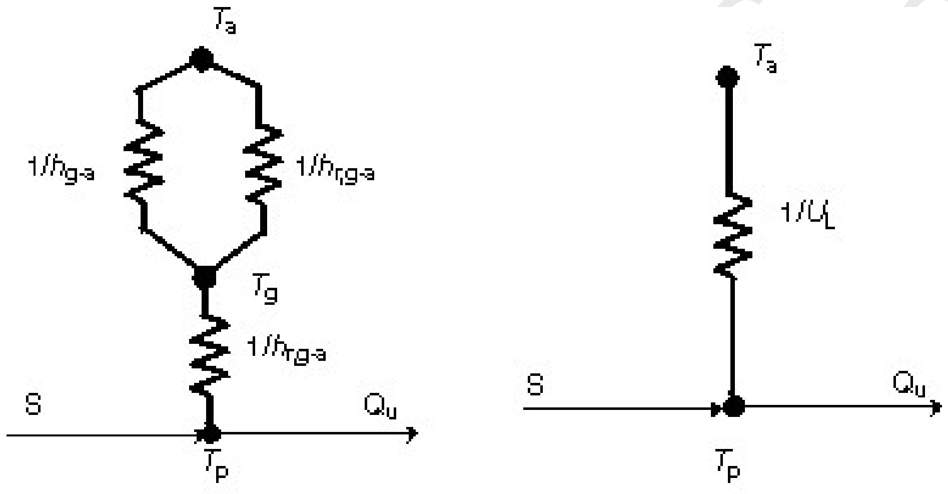
where k is the thermal conductivity of the absorber plate and δ is the plate thickness.

It is useful to develop an overall loss coefficient for a flat plate evacuated tube collector. The analysis follows that for normal flat plate collectors with simplifications introduced by ignoring the conduction and convection heat transfer from the absorber plate to the glass tube since high vacuum normally exists inside the glass tube. The thermal network for the system is shown schematically in Figure 5 At some typical location on the plate where the temperature is T_p, solar energy of amount S is absorbed by the plate; S is equal to the incident solar radiation, reduced by optical losses. This absorbed energy S is distributed to thermal losses through the glass tube and to useful energy gain.

The energy loss from the absorber plate to the glass tube is by radiation only, since conduction and convection heat transfer are inhibited by the vacuum inside the glass tube. The energy loss from the glass tube to the ambient is by radiation and convection. The radiation loss from both sides of the absorber plate to the glass tube can be expressed as (Kreider 1979; Duffie and Beckman 1980)

$$Q_{loss} = \frac{2\sigma\,(T_p^4 - T_g^4)}{\dfrac{1-\varepsilon_p}{\varepsilon_p A_c} + \dfrac{1}{A_p} + \dfrac{1-\varepsilon_g}{\varepsilon_g A_g}} = h_g(T_g - T_a) + \varepsilon_g \sigma\,(T_g^4 - T_s^4) \tag{8}$$

where ε_p and ε_g are the emissivities of the absorber plate and glass tube, respectively, h_g is the convection heat transfer coefficient from the glass tube to ambient air, A_p and A_g are the areas of the absorber plate and glass tube, respectively.



(a) Thermal network for a flat plate evacuated tube collector

(b) Equivalent thermal network.

Figure 5. Thermal network for a flat plate evacuated tube collector.

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