# Temperature Limitation in Evacuated Solar Collector Tubes

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#### Abstract

A recent innovation in evacuated tubular solar collector technology is described. A desorbable gas, which specifically adsorbs on the graphitic solar selective surface, can reversibly degrade the vacuum by providing a heat conduction path at elevated temperatures. The stagnation temperature of the system is thus limited in a controllable manner without significantly degrading the low temperature performance. A simple theory incorporating the Langmuir adsorption isotherm and the Knudsen free molecule transport regime is used to describe the phenomenon.

## 1. Introduction

Solar thermal collectors exhibit three distinct energy flows. Incident energy from solar radiation is absorbed by the collector. As the temperature of the collector increases, energy is lost back to the surroundings. The difference between these two energy flows is the useful energy delivered by the collector.

Energy losses from the collector can occur by three physical processes—conduction, convection and radiation. Radiative energy losses can be reduced by decreasing the emittance of the solar absorbing surface. It is possible to design a surface with low emittance for thermal radiation, whilst still maintaining a high absorptance for solar radiation due to the spectral separation of the solar radiation and thermal radiation at typical operating temperatures. Such a surface is termed 'selective'. A good quality selective surface has a solar absorptance above 90% with an infrared emittance of a few per cent.

Further reductions in the energy losses from solar collectors can be achieved by reducing conduction and convection losses. Maximum reduction occurs when the space surrounding the selective surface is evacuated. In a practical device it is only realistic to achieve this with a vacuum envelope of tubular geometry; such a device is called an evacuated tubular collector.

Evacuated tubular collectors (Window and Harding 1984) have been built in two main generic forms. In one type, the metal-in-vacuum collector, a metal plate is located within a glass tube. Heat absorbed by the plate is transported through the glass walls by a suitable heat extraction system. The other type of evacuated tubular collector is constructed like a Dewar flask, where two glass tubes are mounted concentrically with the intervening space evacuated. The selective surface is located on the outer (vacuum) surface of the inner glass tube. Both types of evacuated tubular collector can achieve extremely low thermal losses. Typically, stagnation temperatures (for no heat extraction from the collector) of around 300°C are observed in non-concentrated sunlight. The existence of such a high stagnation temperature implies an ability for evacuated tubular collectors to supply heat with reasonable efficiencies at temperatures greater than 100°C, well above that possible with most flat plate collectors. The lower losses from evacuated tubular collectors can also result in improved performance for these devices at lower temperatures (less than 100°C), and under adverse conditions such as low solar radiation levels, low ambient temperatures, or in high wind conditions. Indeed, it has been argued (Collins 1982) that it is in this low temperature region that evacuated tubular collectors must find large scale application in order for these devices to be commercially viable.

The good thermal performance of evacuated tubular collectors at low temperatures, and the high stagnation temperatures of these devices, are both a result of the extremely low thermal losses. It would seem, therefore, that these two characteristics are inextricably linked, and that designs of low temperature systems must incorporate measures to protect against the high stagnation temperatures. Such measures usually involve cost and performance penalties. It would clearly be desirable to incorporate features into an evacuated tube which reduced the temperatures reached under stagnation conditions without adversely affecting the low temperature performance.

The work described here addresses this problem and expands on our preliminary report (Pailthorpe *et al.* 1987). Specifically, evacuated tubes have been built in which a small quantity of gas is introduced into the 'vacuum' space during the evacuation process, prior to sealing the tube. At low temperatures most of the gas molecules are adsorbed on surfaces within the tube, principally the selective surface, and a high level of vacuum exists. Thermal losses are therefore essentially unaffected. As the temperature of the selective surface increases, some of the gas molecules desorb from the surface and enter the vacuum space. Re-adsorption of these molecules onto the relatively cool outer glass tube does not occur to any significant extent. The level of vacuum in the tube is thus decreased, resulting in increased thermal losses.

This method of reducing stagnation temperatures in evacuated tubular collectors without significantly affecting low temperature performance has been proposed previously (Harding and Window 1981). However, no significant nonlinear heat losses due to desorbable gas have been reported prior to the present work. The key to this work lies in the identification of a class of gas molecules for which the adsorption on the selective surface varies strongly at temperatures where heat losses are desirable.

This 'selective adsorption' effect depends on the properties of the gas molecules, the glass, the selective surface and, specifically, the outermost atomic layers of this surface. The Sydney University selective surface is about one-third graphitic (McKenzie *et al.* 1983 *a*, 1983 *b*). The glass surface, however, consists principally of oxide and hydroxyl groups. This indicates that a hydrophobic gas species is desirable. Benzene is a suitable choice since its molecules are energetically and geometrically compatible with the graphitic surface. In fact, the gas-surface interaction is expected to be similar to the interaction of benzene with its solid phase. A significant difference is that the selective surface, being deposited by reactive magnetron sputtering, possesses a distribution of higher energy sites due to the presence of dangling bonds etc. (Miller and McKenzie 1983). This feature is important for the practical aspects of the technology. In addition, it offers scope for fundamental research in gas adsorption

onto energetically heterogeneous surfaces in the very low pressure regime, a field in which only now is significant progress being made.

Evacuated collector tubes have been built which exhibit enhanced heat losses at high temperatures due to desorbed gas molecules. A simple kinetic theory calculation has been made which relates the heat losses in such tubes to the adsorption-desorption processes. The theory indicates how the heat losses may be made to increase more rapidly with temperature (increasing the sharpness of the 'thermal switch'). In addition, the theoretical analysis provides insight into the type of ageing experiments which should be performed in order to demonstrate the stability of the adsorption-desorption process over long periods of time.



Fig. 1. Dewar flask evacuated tubular solar collector showing (a) the annular vacuum gap and path for heat loss and (b) a schematic representation of the system for gas adsorption analysis.

In the present work, the outer glass envelope of a collector tube is held at constant temperature, usually close to ambient temperature. In a practical solar collector tube operating under stagnation conditions, the thermal impedance due to cooling by air of the outer glass tube results in the temperature of the tube being significantly above ambient. This aspect of the system is under further study.

## 2. Theory

The presence of gas molecules in an evacuated tube results in enhanced heat transport as the temperature of the selective surface increases. The system, illustrated in Fig. 1, is not at equilibrium due to the imposed temperature gradient. However, during steady state operation the system is not far from equilibrium. The approach adopted here factors the problem into two parts and is essentially a first order perturbation theory. First, the state of the system is described by an equilibrium theory of the gas adsorption process at some 'average' temperature T. Second, the heat transport processes are discussed in terms of the available number of gas molecules in the gas phase (i.e. the system pressure p), as prescribed by the equilibrium theory. At low pressure, the heat transport coefficients depend on the state of the gas phase only via  $p/T^{1/2}$ . Fortunately, kinetic theory predicts that  $p/T^{1/2}$  is constant throughout the system, at least for molecules with a Maxwellian distribution of velocities (Kennard 1938). The second assumption, however, represents a significant limitation of our approach.

## Heat Transport

Heat transport in gases has been thoroughly studied (Maxwell 1860, 1879; Smoluchowski 1911; Knudsen 1911, 1934; Kennard 1938) and the results are simply summarised here. At low pressures, when the mean free path of the molecules is much greater than the dimensions of the vacuum space, the gas molecules move from the hot to cold surface without a significant number of collisions. The heat flux between concentric cylindrical or spherical surfaces is found to be

$$H = \alpha A \frac{\gamma + 1}{\gamma - 1} \left(\frac{R}{8\pi}\right)^{\frac{1}{2}} \frac{p}{(NmT)^{\frac{1}{2}}} (T_{\rm I} - T_{\rm O}), \qquad (1)$$

where *H* is the net energy transfer per unit time, *A* is the area of the inner surface,  $\gamma = C_p/C_v$  is the ratio of specific heats, assumed constant, *m* is the molecular mass of the gas, *R* is the universal gas constant, *N* is Avogadro's number, *T*<sub>I</sub>, *T*<sub>O</sub> are the temperatures of the inner and outer surfaces respectively, *A*<sub>I</sub>, *A*<sub>O</sub> are the areas of these surfaces, and

$$\alpha = \frac{\alpha_{\rm I} \alpha_{\rm O}}{\alpha_{\rm O} + \alpha_{\rm I} (1 - \alpha_{\rm O}) A_{\rm I} / A_{\rm O}}$$
(2)

is the overall accommodation coefficient, defined in terms of the accommodation coefficients at the surfaces. The derivation of (1) requires careful counting of multiple transits of gas molecules between the two surfaces and a calculation of the average energy transfer during gas-surface collisions (Corruccini 1959). The accommodation coefficient at either surface is defined as the fraction of maximum possible energy exchange that a molecule makes on average when it collides with the surface. These coefficients can be determined empirically using (1), as reported for surfaces in evacuated tubular collectors by Harding and Window (1981). A more fundamental approach, such as atom-surface scattering experiments (Goodman and Wachman 1976), can be useful and of basic significance, but is experimentally difficult to undertake.

In equation (1) the temperature T and pressure p require definition. The gas molecules within the concentric space are not in thermal equilibrium with either of the surfaces. Some insight is provided by Maxwell's (1879) picture in which a fraction  $\alpha$  of incident molecules thermally equilibrate with the surface, while the remaining fraction  $1-\alpha$  are specularly scattered with negligible energy exchange. At low pressures, a system similar to that shown in Fig. 1a then contains two intermixed Maxwellian streams of molecules: one characterised by a temperature  $T_1$ , the other by  $T_{\rm O}$ . In the system discussed here, our best estimate is that about 75% of the gas molecules are at  $T_{\rm I}$ , while 25% are at  $T_{\rm O}$ . The free molecule (low pressure) regime occurs in our system only for temperature differences up to 50-100°C. Thus, the average velocity of the two Maxwellian distributions in the system varies by only about 10%. In order to make further progress we adopt the reasonable approximation that a single equilibrium temperature characterises the gas, an approximation which should not qualitatively affect our understanding of the physics of this system. A more rigorous approach requires solution of the Boltzmann equation (Cercignani 1975), a substantial research project in its own right.

For gases in the free molecule regime at steady state, however, it is easy to show that the flux of molecules is equal in each direction along a tube connecting the concentric space to an isothermal enclosure. This leads to the relationship

$$pT^{-\frac{1}{2}} = \text{constant} \tag{3}$$

for any point in the sealed system. Thus p and T in (1) and (3) may be taken to be values measured in an isothermal enclosure which is attached to the heat loss device.

At high pressures, when the mean free path for gas molecules is much smaller than the dimension of the concentric gap (see Fig. 1*a*), the heat flow is almost independent of pressure. (The effect of the larger number of molecules is almost exactly balanced by the decreased distance between molecular collisions.) In this case, the gas at any point in the tube can be characterised by a well-defined temperature and the situation can be analysed by elementary considerations in terms of a well-defined thermal conductivity K:

$$H = 2\pi L K (T_{\rm I} - T_{\rm O}) / \ln(r_{\rm O}/r_{\rm I}), \qquad (4)$$

where L is the length and  $r_{\rm I}$  and  $r_{\rm O}$  are the radii of the inner and outer cylinders respectively. Values of the thermal conductivity K are tabulated for many gases (Ražnjević 1976) and, for the pressure regimes considered here, can also be calculated from elementary kinetic theory:

$$K = \frac{25}{32} \left(\frac{kT}{\pi m}\right)^{\frac{1}{2}} \frac{C_{\rm v}}{N\sigma^2},\tag{5}$$

where k is Boltzmann's constant,  $\sigma$  is an effective hard sphere diameter for the gas molecules (McQuarrie 1976), and  $C_v$  is the constant volume molar heat capacity.

The change from the free molecule to the hydrodynamic regime is determined by the mean free path

$$\lambda = k T / \sqrt{2 \pi \sigma^2 p}. \tag{6}$$

Equation (1) applies when  $\lambda \ge d$  and (4) applies when  $\lambda \ll d$ , where the annular gap dimension is  $d = r_0 - r_1$  (Fig. 1*a*). The transition between the two transport regimes can be characterised experimentally, as discussed below, but is less understood theoretically due to the intractability of the Boltzmann equation (Cercignani 1975).

In order to determine the temperature dependence of heat losses from an evacuated tube, we must therefore calculate the way in which the pressure in the tube changes with temperature.

## Gas Adsorption

As discussed above, it is not possible to define an equilibrium temperature or pressure in the region between the hot and cold surfaces of an evacuated tube. This complicates the analysis of the interaction between gas molecules in the vapour and condensed phases. In order to develop an understanding of this process, we therefore first consider the situation where all temperatures in the system are uniform. The results of this analysis provide significant insights which can subsequently be generalised to the case where the temperature is non-uniform.

It is further necessary to introduce a model of the adsorbed gas phase. In this discussion we adopt the simplest such model, that of the lattice gas (Langmuir 1918; Hill 1960) in which adsorbed gas molecules are immobilised onto distinguishable, fixed, energetically uniform surface sites. Only one molecule can occupy each site, and the model is therefore restricted to surface coverage of up to one monolayer. The various extensions of this model have been extensively studied (Gregg and Sing 1985) and are well understood. They are, however, not relevant to our system since the pressures of interest occur for surface coverages which are considerably less than one monolayer.

The most restrictive approximation in this model is that of an energetically uniform surface. Our surface is fabricated by sputtering, which guarantees the presence of a wide distribution of site energies. Only recently, however, has significant progress been made in the relevant theory for adsorption on such surfaces (L. R. White, personal communication 1986). High quality adsorption data at low (ultra-high vacuum) pressures are still required.

In the following we adopt a kinetic theory approach (Langmuir 1918; de Boer 1968) rather than using equilibrium statistical thermodynamics (Hill 1960). The steady state nature of the problem is thus highlighted and the key physical concepts are explicit. The details of the argument are given since this illustrates the method of solution of the full non-isothermal problem and the system is novel.

We consider a volume V with a surface of area A which can interact with the adsorbing and desorbing gas molecules (Fig. 1b). All other surfaces in this system are assumed not to interact with the molecules. We assume that there are  $N_{\text{TOT}}$  gas molecules in the system, the number adsorbed on the surface is  $N_A$  and the number in the gas phase is  $N_G$ . The system operates at relatively low pressures (<10 m Torr = 1.33 Pa) so that the ideal gas equation of state gives

$$pV = N_{\rm G} kT = (N_{\rm TOT} - N_{\rm A})kT.$$
(7)

The number of molecules desorbing from the surface per unit time is given by

$$R_{\rm OUT} = \nu(T) N_{\rm A} \,, \tag{8}$$

where  $\nu$  is the probability of desorption of an individual molecule per unit time. (We assume that  $\nu$  is independent of the number of molecules, which is equivalent to ignoring cooperative effects or effects associated with nearly complete coverage or multiple adsorbed monolayers.) Since desorption is a thermally activated process the dominant temperature dependence is given by

$$\nu(T) = Y \exp(-E/kT), \qquad (9)$$

where Y is a rate constant roughly characterising molecular vibration normal to the surface (de Boer 1968), and E is an activation energy which can be interpreted as the energy depth of a trapping site.

The number of molecules incident on the surface per unit time is given by elementary kinetic theory as (Kennard 1938)

$$N_{\rm IN} = nvA/4, \tag{10}$$

where n is the number of molecules per unit volume, the mean molecular speed is

$$v = (8 k T / \pi m)^{\frac{1}{2}}, \qquad (11)$$

and m is the mass of a gas molecule. Using (7) we can thus show that

$$N_{\rm IN} = pA(2\pi m k T)^{-\frac{1}{2}}.$$
 (12)

If  $\mu$  is the probability of adsorption of a molecule striking a vacant site on the surface, the number of molecules adsorbed per unit time is given by

$$R_{\rm A} = N_{\rm IN} \,\mu (1 - N_{\rm A}/M), \tag{13}$$

where M is the total number of sites on the surface at which adsorption can occur, and where it is assumed that adsorption of an incident molecule is only possible on a vacant site.

At equilibrium, or in steady state, the rates of adsorption and desorption of moleules at the surface are equal, and thus

$$\nu N_{\rm A} = p A \mu (2\pi \, m \, k \, T)^{-\frac{1}{2}} (1 - N_{\rm A} / M) \,. \tag{14}$$

This equation can be rewritten in the standard form

$$N_{\rm A} = \frac{M \ b(T)p}{1 + b(T)p},$$
(15)

where

$$b(T) = A\mu/M(2\pi mkT)^{\frac{1}{2}}\nu(T).$$
(16)

Equation (15) is the well-known Langmuir adsorption isotherm. The coefficient b(T) is also available from equilibrium statistical mechanics (Hill 1960):

$$b(T) = \left(\frac{h^2}{2\pi m k T}\right)^{\frac{3}{2}} \frac{\exp(-E/kT)}{kT} \frac{q_{\rm A}(T)}{q_{\rm G}(T)},\tag{17}$$

where h is Planck's constant and  $q_A$  and  $q_G$  are the internal partition functions for molecules in the adsorbed and gaseous phases respectively. Equation (17) allows correlating the adsorption and desorption probabilities with molecular properties. Equilibrium adsorption experiments (Young and Crowell 1962; Gregg and Sing 1985) at constant pressure can be used to measure b(T) and hence E.

Combining (7) and (15) yields the desired expression for the pressure in our system:

$$\frac{V b(T)}{k T} p^2 + \left( b(T)(M - N_{\text{TOT}}) + \frac{V}{k T} \right) p - N_{\text{TOT}} = 0.$$
 (18)

An alternative form of this equation,

$$N_{\rm G} bp + b(M - N_{\rm TOT})p - N_{\rm A} = 0, \qquad (19)$$

provides useful insights. At 'low' temperatures and for relatively small volumes almost all molecules are adsorbed ( $N_A \approx N_{TOT}$ ) and, since in practice  $M \gg N_{TOT}$ ,

$$p \approx N_{\text{TOT}} / M b(T) \approx \exp(-E/kT).$$
 (20)

Under these conditions, it is apparent that the gas pressure varies exponentially with temperature. At first sight, it is surprising that this expression for p does not include the volume V; however, this is indeed what does occur. As the volume decreases, individual molecules in the gas phase make more collisions per unit time with the surface, at constant pressure. Thus, the number of molecules *per unit volume* remains constant. Note that this is only the case provided that most of the molecules are adsorbed. Under these conditions, the situation is analogous to that of a saturated vapour above a liquid; the saturated vapour pressure, which is proportional to the number of atoms per unit volume, is independent of the volume of vapour.

At 'high' temperatures when  $\nu$  is large (and thus b is small), or when V is very large, only the last two terms in (18) are significant. Most of the gas is then desorbed and  $pV \approx N_{\text{TOT}} k T$ .

## 3. Experimental Work and Discussion

## Vacuum Systems

Evacuated tubular collectors are conventionally pumped out on a standard vacuum system consisting of an oil diffusion pump and a rotary backing pump. During evacuation, the tube is heated to high temperature (about 500°C in our case) to remove adsorbed and absorbed gas from internal surfaces. A schematic diagram of the equipment used is shown in Fig. 2*a*. Normally the tube is allowed to cool for a few minutes following removal of the bakeout oven before sealing the pump-out stem. Tubes of 1.4 m length and nominal power rating 45 W were fabricated as previously described (Window and Harding 1984).

In our work, a small amount of gas can be admitted into the tube during the cooling process by two methods. In one method (Fig. 2b), gas is admitted at constant pressure ( $\approx 0.1$  Torr) from a previously degassed liquid (Analytical Reagent grade, 99.7% pure benzene). The rate of admission is controlled by a needle valve. Gas is also continually removed from the system by the pumps. It is necessary to introduce a constriction into the pumping line during this process to prevent the diffusion pump stalling at the relatively high operating pressures. In this method, the total quantity of gas in the evacuated tube is determined by the pressure as measured outside the tube, and by equation (3), provided that negligible adsorption occurs on the surfaces of the tube prior to seal-off. The latter condition is expected to be satisfied at typical seal-off temperatures of  $\approx 250^{\circ}$ C.



Fig. 2. Schematic illustration of the evacuated tube fabrication procedure: (a) no desorbable gas present; (b) the tube is exposed to gas at a constant pressure; and (c) a known quantity of gas is dosed into the tube via a calibrated volume.

In the second method (Fig. 2c) for admitting desorbable gas, a small container of known volume is filled with gas at a known pressure. The evacuated tube is then valved off from the vacuum pumps and the line between the tube and the container is opened. Gas molecules are rapidly distributed between the container and the tube, and the tube is then sealed off. Under these conditions, if the volume of the container is small compared with the evacuated tube, the number of molecules in the evacuated tube is relatively insensitive to the temperature at the time of sealing even if significant

adsorption occurs. This latter method is thus likely to be more controllable and would be preferable in a high volume manufacturing process.

The dosing technique illustrated in Fig. 2c can be used as a standard technique to measure adsorption isotherms, namely  $N_A(p, T)$  by equation (15). Small quantities of gas are sequentially admitted to the tube and the pressure monitored. The pressure in the metered volume provides a direct measure of the quantity of gas adsorbed by the selective surface. In addition, the change in pressure with time can provide information on the kinetics of adsorption, although this is at the limits of resolution of the present apparatus. The adsorption process occurs over a timescale of seconds.



Fig. 3. Benzene adsorption isotherms measured using the apparatus in Fig. 2*c* and showing the number of adsorbed gas molecules versus gas pressure at fixed temperature. The insert shows standard isotherms for benzene adsorbed on graphite baked at 2700°C. Note the difference in pressure scales. Tube dimensions are  $r_{\rm I} = 15$  mm,  $r_{\rm O} = 19$  mm and L = 1.45 m.

A family of adsorption isotherms for benzene on the graphitic selective surface is shown in Fig. 3. The isotherms show the classic Langmuir form (15), and no evidence of multilayer adsorption is observed up to pressures of about 60 mTorr. Separate adsorption experiments on all-glass tubes with no graphite surface indicate that, at 20°C, the quantity of gas adsorbed onto glass is about 10% of that onto the selective surface. The data of Fig. 3 imply that the number of surface sites is  $M = 1.0 \times 10^{19}$ . Taking the known adsorption area of a single benzene molecule as 49 Å<sup>2</sup> (Pierotti and Smallwood 1966) indicates that the surface area presented for benzene adsorption is about 40 times larger than the apparent geometric area. In addition, use of (9) and (15) yields the representative surface interaction energy as E = 0.4 eV, or about 15kT, at ambient temperature. This indicates strong physisorption which presumably has its origins in the unusually large electronic polarisability of the benzene molecule. The quantity of gas admitted into a typical temperature limited evacuated tubular collector is such that the pressures are at all times less than  $\sim 1$  mTorr, corresponding



**Fig. 4.** Schematic illustration of the experiment for measuring heat losses from an evacuated tube. An electrically heated aluminium slug is fitted within the inner glass tube to provide thermal mass and to ensure that the selective surface is isothermal.



Fig. 5. Heat loss measured as a function of temperature in gas loaded collector tubes (nominal rating 45 W). The radiation loss (dashed curve) is shown for comparison. Combined radiation and conduction loss is shown for tubes charged with fixed quantities of gas and sealed at  $250^{\circ}$ C with (A) 0.04, (B) 0.07 and (C) 0.1 Torr benzene. Tube dimensions are as in Fig. 3.

to a surface coverage of about 3% of a monolayer. Such tubes typically contain about  $10^{17}$  molecules of desorbable gas.

# Heat Loss from Tube

Measurements of the rate of heat loss from evacuated tubes were made in the apparatus illustrated in Fig. 4. The outer tube is enclosed in a water jacket held at constant temperature, and heat is supplied to the inner tube by an electrical element. The temperature of an approximately isothermal sheath surrounding the heating element is measured by a thermocouple as the temperature of the tube varies during heating and cooling.

The thermal mass of the inner tube and heating apparatus can be determined by supplying a known amount of energy to the electrical heater and measuring the resultant temperature change once equilibrium is reached. This calorimetric method is quite accurate at low temperatures where tube losses are small. Once the thermal mass of a tube and heater has been determined, variations in temperature of the isothermal sheath can be related to heat losses from the tube.

Typical results for heat losses from gassy evacuated tubes are shown in Fig. 5. Also shown are the radiative heat losses from a similar tube with high vacuum. The difference between the total loss and the radiative losses represents the heat losses due to the desorbable gas.

It can be seen that the heat losses due to desorbable gas are nonlinear with temperature, indicating that the pressure within the tube is varying. It is also noted that the temperature above which significant gas losses occur increases with the total amount of desorbable gas in the tube.

Measurements of heat loss during heating and cooling give identical results to within experimental accuracy. The absence of hysteresis in these data sets a lower limit on the characteristic times associated with the adsorption and desorption process, at least for low pressures. These times are certainly less than several minutes. It does indicate, however, that other processes such as diffusion of adsorbed molecules into the surface due to porosity are either not present, or also occur quite rapidly. On a more pragmatic level, the similarity between thermal losses during heating and cooling is a useful (perhaps essential) characteristic for the utilisation of these tubes in practical systems.

Another feature of the process which is important for practical applications is longterm stability. We have aged tubes for over six months under stagnation conditions in full sunlight and have not observed any variation in heat loss characteristics. Further ageing work remains to be done, particularly relating to the identification of possible ageing mechanisms and the design and implementation of experiments to accelerate ageing which depends on such mechanisms. In particular, ageing experiments require accurate heat loss data in the low pressure region where the heat loss is most sensitive to pressure.

## Pressure in the Tube

It is difficult to relate heat loss data such as shown in Fig. 5 to the pressure of gas within the evacuated tube, because no information is available on the accommodation coefficient. In order to obtain an indication of the magnitude of the gas pressure,

heat loss measurements were made on a single evacuated tube whilst still connected to the evacuation apparatus. During the measurements, the pressure of benzene gas in the system was maintained at a steady value (see Fig. 6).



Fig. 6. Calibration of heat loss versus gas pressure measured using the techniques illustrated in Figs 2b and 4. Tube dimensions are  $r_{\rm I} = 20$  mm,  $r_{\rm O} = 25$  mm and L = 1.75 m.

The experimental heat loss versus pressure calibration shown in Fig. 6 facilitates a comparison of observed 'cool-down' data (see Fig. 5) with the theory presented above. In Fig. 7 the predictions of (18) are compared with the data for four values of the activation energy E. The value of 0.5 eV ( $\approx 15 kT$ ) is appropriate for standard benzene on graphite adsorption (Pierotti and Smallwood 1966) and for the benzene vapour pressure curve. It is also consistent with the high coverage data presented in Fig. 3. However, only much higher energies around 0.7 eV are consistent with the heat loss measurements. These refer to low coverages which are not resolved in Fig. 3, and where perhaps higher energy sites are presented for adsorption, a result which is being investigated further. It certainly indicates that the surface is very heterogeneous, with perhaps 10% of very high energy (0.7 eV) adsorption sites, and the remainder with adsorption energies around 0.4 eV.

The results shown in Fig. 6 provide important information about the order of magnitude of the gas pressure in the tube. The heat losses are seen to be highly nonlinear with gas pressure. This indicates that the pressure of gas within the tube quickly rises as the temperature increases to levels where the mean free path for molecule-molecule collisions is less than the gap between the tubes. Under such conditions, the magnitude of the heat losses is limited by the high pressure thermal conductivity of the gas and by the tube geometry.

It is immediately obvious how to increase the sharpness of the thermal switch in gassy evacuated tubes: the gap between inner and outer tubes must be decreased. This will cause the tube to operate in the low pressure domain (mean free path less than gap between tubes) up to higher pressures. It also increases the thermal conductance of the gas at high pressures due to the lower gap. Perhaps most significantly, however, this is achieved without affecting the behaviour of the heat losses at low pressures since, as (20) shows, the gas pressure is independent of volume under these conditions.



Temperature of selective surface (°C)

Fig. 7. Heat loss versus temperature for a gassy evacuated tube. Data points are compared with the predictions of equation (18) using various estimates of the activation energy E. The calibration shown in Fig. 6 facilitates the comparison.

The considerably improved characteristics of the thermal switch with a very narrow gap have important implications for the practical application of this technique. It is clearly well suited for Dewar-type evacuated tubes, and its usefulness increases as the gap decreases. The technologically achievable lower limit on gap is determined by dimensional tolerances on the glass tubing particularly relating to tube straightness. For gaps less than 3 mm in evacuated tubes 1.5 to 2 m in length, a straightening operation may be necessary.

The technique is also relevant to metal-in-glass collectors with flat absorbers [e.g. as manufactured by Philips, Sanyo and Corning (France)]. As presently constructed, these devices have an effective gap of several cm. Equivalent behaviour to Dewar-type collectors could be obtained, however, if curved absorbers were used in these tubes so that the stagnating surface was positioned very close to the outer glass tube (see e.g. Pailthorpe and Collins, Australian Patent Application No. PH04009).

#### Future Work

The work discussed here continues and, in particular, an analysis is being made of the behaviour of temperature limited evacuated collector tubes in an operating solar collector. In such a situation, the heat loss from the outer glass tube to the surroundings is through conduction, convection and radiation, and the temperature of the tube is above ambient. The behaviour of the pressure in the tube can be influenced by adsorption on the outer glass tube under these conditions and this phenomenon is being studied more closely.

It is not clear why the adsorption isotherms on our selective surface (Fig. 3) show saturation at substantially lower pressures than that observed for benzene on graphite, while indicating essentially the same activation energy (0.4 eV) for most of the adsorbed molecules. It is not clear if the heterogeneity of the surface can account for such behaviour. It is possible that the apparent roughness of the surface on a microscopic scale may play a role, but we can offer no plausible explanation at this time. Adsorption isotherm data at low pressures in ultra-high vacuum equipment at present under construction may help to resolve this difficulty.

#### 4. Conclusions

It has been demonstated that, using desorbable gas, it is possible to reduce significantly the stagnation temperature of an evacuated tube with minimal increase in the heat losses at low temperatures. Our understanding of the physical processes involved in the heat loss from such tubes indicates that the transition between the low temperature, low loss region and stagnation conditions can be made to occur over a relatively narrow range of temperatures. Tubes have been built which stagnate at temperatures below 120°C.

These results have raised promising possibilities for solar system design utilising evacuated tubular collectors. It appears possible to incorporate mechanisms to protect against high stagnation temperatures within the evacuated tube, without degrading the low temperature performance, and thereby significantly reducing the cost and complexity of the overall system design. This development could therefore significantly enhance the commercial viability of evacuated tubes in low temperature applications, such as domestic hot water systems.

Considerable work remains to be done to demonstrate the viability of this method in practical systems. For example, degradation mechanisms such as gas decomposition or changes in the morphology of the surface must be studied to determine whether the characteristics of the thermal switch are stable over long periods. Initial ageing measurements have failed to show any changes in heat loss behaviour. Our present theoretical understanding of the process indicates that such changes, if they occur, will first be evident in the behaviour of the heat losses at low temperatures. Only in this region are losses strongly dependent on gas pressure.

Very little is known about the actual adsorption process. We have initiated work on this process under closely controlled (ultra-high vacuum) conditions. The study of adsorption and desorption phenomena under such conditions will assist in the optimisation of the design of evacuated tubes incorporating desorbable gas. It should also provide valuable insight into the fundamental adsorption-desorption process in the important, and relatively inacessible, low pressure region. In particular, accurate gas adsorption isotherms at very low pressures can uniquely characterise the distribution of surface site energies, which has hitherto been unavailable.

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