

## Molecular heat transfer in rarefied gas: experimental determination of thermal accommodation coefficients

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### Abstract

Molecular heat transport in rarefied gas can be a significant factor in the thermal system performance of vacuum applications. An experimental setup is realized to measure the relation between gas pressure and heat transfer coefficient, which is determined by the thermal accommodation coefficient. The influence of surface contamination on the thermal accommodation coefficient is investigated and found to be of significant impact on the heat transfer performance.

Thermal accommodation coefficient, vacuum, Sherman-Lees, rarefied gas, surface adsorption, monolayers, heat transfer coefficient

### 1. Introduction

Thermal management under vacuum conditions can be crucial in the performance of high-precision equipment. Two heat transfer mechanisms play a role in heat transport through a vacuum: thermal radiation and molecular heat transport. Especially at ambient temperatures (or lower) and when there is a considerable amount of gas (few Pascal and higher), the molecular heat transport will dominate the overall heat transfer rate.

Unlike in continuum conditions, the heat transfer coefficient in the free molecular regime is dependent on the gas pressure as well as on various gas and surface properties. This heat transfer process is illustrated in Figure 1: an incident gas molecule with temperature  $T_i$  interacts with a solid surface with (constant) temperature  $T_s$ , thereby exchanging energy such that the temperature of the reflecting molecule has changed to  $T_r$ .

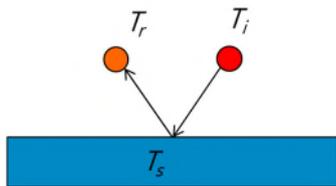


Figure 1. Illustration of molecular heat transfer process.

The efficiency of this molecular heat transport is expressed by means of the thermal accommodation coefficient  $\alpha$ :

$$\alpha = \frac{T_r - T_i}{T_s - T_i}$$

The thermal accommodation coefficient is an important model parameter to predict the heat transfer rate. For two parallel solid plates with an intermediate gas medium, a commonly used model that describes the relation between heat transfer coefficient and gas pressure is the so-called Sherman-Lees relation [1], [2]:

$$\frac{1}{h_g} = \frac{d_g}{\lambda_g} + \frac{2 - \alpha}{\alpha} \cdot \frac{\sqrt{\frac{\pi M_g T}{2R}}}{\left(1 + \frac{\zeta}{4}\right) p} \quad [\text{Eq. 1}]$$

with  $h_g$  the heat transfer coefficient between the two parallel plates,  $d_g$  the distance between the plates,  $\lambda_g$  the continuum gas conductivity,  $M_g$  the gas molecular mass,  $R$  the universal gas constant,  $\zeta$  the atomic degrees of freedom of the gas,  $T$  the gas temperature and  $p$  the gas pressure. Figure 2 shows an example result of the Sherman-Lees relation for nitrogen and a 300  $\mu\text{m}$  gap size with pressure on the horizontal axis and gap heat transfer coefficient on the vertical axis. Note that the heat transfer coefficient approaches a constant value for pressures inside the continuum regime whereas in the free molecular regime a clear pressure dependency can be observed.

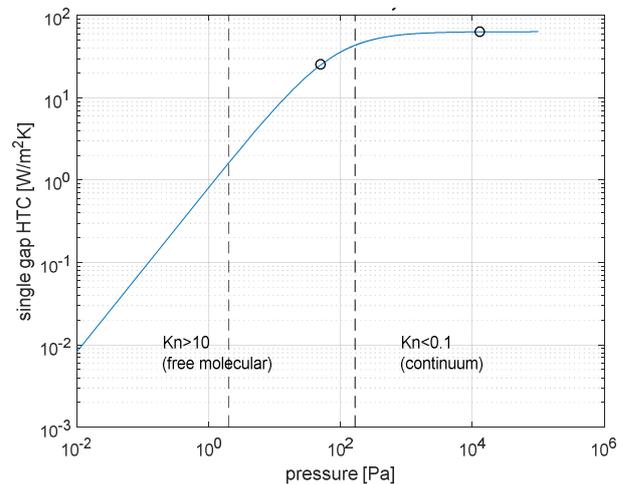


Figure 2. Result of Sherman-Lees relation for nitrogen at a 300  $\mu\text{m}$  gap size.

It is apparent that knowledge on the thermal accommodation coefficient  $\alpha$  is essential to predict the relation between heat transfer coefficient and gas pressure. However,  $\alpha$  is dependent on both gas and surface characteristics such as surface material, surface roughness, gas composition, cleanliness of the surface (i.e., adsorbed monolayers) and much more. In literature, some generic values  $\alpha$  can be found for limited cases. For instance, comparable work has been performed at Sandia National Laboratories [3]. For practical applications where accurate

thermal modelling is required, the thermal accommodation coefficients needs to be determined for each specific situation.

The current work describes the development of an experimental setup at Philips Innovation Services to determine the thermal accommodation coefficient for different solid surfaces under a controlled gas composition and gas pressure. The focus is to achieve high accuracy on reproducibility (typically  $1\%3\sigma$ ) to be able to perform comparative measurements. In Section 2 the measurement principle and realized experimental setup is described. Section 3 is devoted to a brief discussion on measurement results. Finally, some conclusions are drawn in Section 4.

## 2. Experimental setup

An experimental setup is designed to realize and measure a steady-state heat flow in a slit between two parallel surfaces while controlling the gas conditions in the slit. The measurement principle is shown in Figure 3. The heat flow between the surfaces is induced by the temperature difference of the plenums that are water-conditioned at  $35^\circ\text{C}$  and  $15^\circ\text{C}$ . On the centre axis of each plenum, two temperature sensors (Amphenol SC30 NTC's) are embedded ( $T_1, T_2$  and  $T_3, T_4$ ).

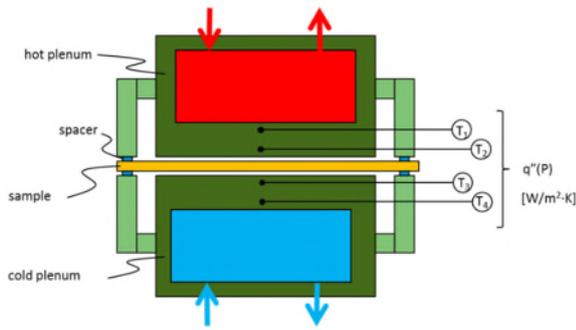


Figure 3. Schematic of measurement principle.

From the measured temperature difference, the mutual distance of the temperature sensors, and the thermal conductivity of the plenum material, the heat flux  $\dot{q}$  through a plenum is calculated. Under the assumption of a purely one-dimensional heat flux (see Section 2.3), the heat transfer coefficient through the gap  $h_g$  can be calculated from:

$$h_g = \frac{\dot{q}}{T_{s,top} - T_{s,bot}} \quad [\text{Eq. 2}]$$

with  $T_{s,top}$  and  $T_{s,bot}$  the surface temperatures of the top and bottom plenum, respectively. These temperatures are obtained through extrapolation from the measured temperatures. This measurement is carried out at two different pressure set points, typically at 50 Pa and 13000 Pa (see Section 2.2). As such, the thermal accommodation coefficient can be derived independent of the actual gap height (see Eq. 1).

### 2.1. Sample measurement

So far, this explains the measurement principle for a single gap (plenum-to-plenum). In order to examine various surface materials, a sample can be placed in between the two plenums (as depicted in Figure 3) and is typically spaced at  $400\ \mu\text{m}$  with respect to the plenum surfaces using ceramic studs (light green in Figure 3) and stainless steel spacers with a variable thickness. The gap height is a trade-off between temperature signal and mechanical tolerances. Consequently, two slits exist on either side of the sample and the Sherman-Lees relation can be extended accordingly to:

$$\frac{1}{h_g} = 2 \cdot \left( \frac{d_g}{\lambda_g} + \frac{\alpha_p + \alpha_s - \alpha_p \alpha_s}{\alpha_p \alpha_s} \cdot \frac{\sqrt{\frac{\pi M_g T}{2R}}}{\left(1 + \frac{\zeta}{4}\right) p} \right) + \frac{d_s}{\lambda_s} \quad [\text{Eq. 3}]$$

with  $d_s$  and  $\lambda_s$  the thickness and thermal conductivity of the sample, respectively. The plenum-to-plenum thermal accommodation coefficient  $\alpha_p$  is used as an input to finally derive the thermal accommodation coefficient for the sample,  $\alpha_s$ .

### 2.2. Gas control

The setup as shown in Figure 3 is placed inside a vacuum vessel (CF DN160 6-way cross) that is equipped with a pump set (Pfeiffer HiPace80 turbo-molecular pump and Adixen ACP15 pre-pump). Two pressure sensors are mounted on the vessel, each covering a different measurement range (MKS Baratron 0 – 133 Pa and 0 – 13300 Pa). The 13000 Pa pressure set point is realized by filling the vacuum vessel with a carrier gas and then carrying out the temperature measurement. For the 50 Pa set point, a continuous flow of carrier gas is provided to the vacuum vessel and pumped away through the pumping system at approximately  $190\ \text{mL}_n/\text{min}$ . The flow rate is controlled using a mass flow controller (Bronkhorst F-201CV-200) and regulated using a control feedback loop with the pressure sensors to maintain a constant pressure throughout the measurement.

Next to the carrier gas flow, also traces of different components can be added to the gas stream in order to investigate the effect of surface monolayer adsorption on the thermal accommodation coefficient. Liquid substances (such as water) are evaporated using a Bronkhorst CEM system prior to mixing-in. A simplified flow diagram of the gas supply system is shown in Figure 4. To realize a dynamic range of partial pressure from  $1 \cdot 10^{-4} - 1\ \text{Pa}$  at a total pressure of 50 Pa, an optional dilution step is added (MFC2 in Figure 4) while the remainder of the mixed gas flow is vented.

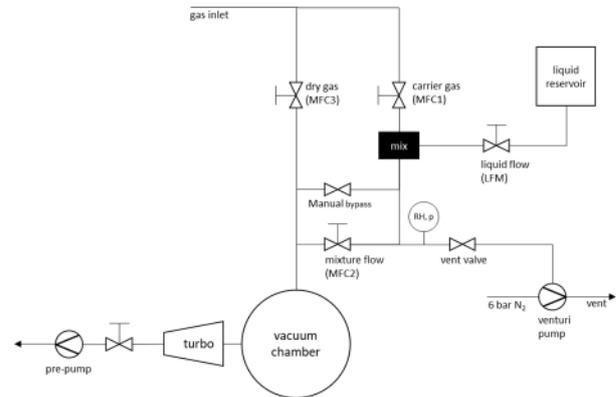


Figure 4. Simplified flow diagram of gas supply system.

### 2.3 Parasitic heat fluxes

The measurement principle is based on the assumption of one-dimensional heat flux through the plenums and no cross talk with other parts of the experimental setup. In reality, there will be a certain amount of heat transfer between the plenums and the vacuum vessel walls. This does result in an offset in the temperature difference measurement from both plenums. To minimize the impact of environmental temperature variations on the measurement reproducibility, the vacuum vessel walls are water-conditioned at  $25^\circ\text{C}$ . As the residual parasitic heat flux to both plenums is comparable, the influence on the heat transfer measurement is largely mitigated by averaging the heat flux measurements from the top and bottom plenums.

### 3. Results and discussion

As a first step in order to quantify the setup measurement reproducibility, five consecutive measurements on the same sample are performed over a time span of two weeks (including sample mounting and removal) using nitrogen as a carrier gas. The relative difference in  $\alpha_s$  with respect to the average value is depicted in Table 1. This results in a determined measurement reproducibility of  $1.1\%3\sigma$ .

**Table 1** Variation in  $\alpha_s$  for five consecutive measurements using nitrogen.

Number	$\Delta\alpha_s$ [%]
1	0.07 %
2	0.13 %
3	-0.51 %
4	-0.27 %
5	0.58 %

One of the key questions in this research is the impact of surface cleanliness on the thermal accommodation coefficient. As such, the difference between various metal engineering samples “as received” and after an additional cleaning procedure is measured, both using nitrogen as carrier gas. The cleaning procedure constitutes of a wipe with iso-propanol followed by a vacuum bake-out procedure of 24hr at 120 °C. Afterwards, the sample is transported from the collocated bake-out facility to the measurement setup. An in-situ bake-out would be more effective in removing water monolayers from the sample, but is not possible due to temperature limitations on the sensors in the setup.

Table 2 shows the change in thermal accommodation coefficient before and after this cleaning procedure. In general, there is a clear decay in  $\alpha_s$  visible. This can potentially be attributed to the removal of hydrocarbons from the sample surface, originating from coolants used in machining steps. The impact of cleaning is very variable for the different samples, probably due to differences in the manufacturing processes.

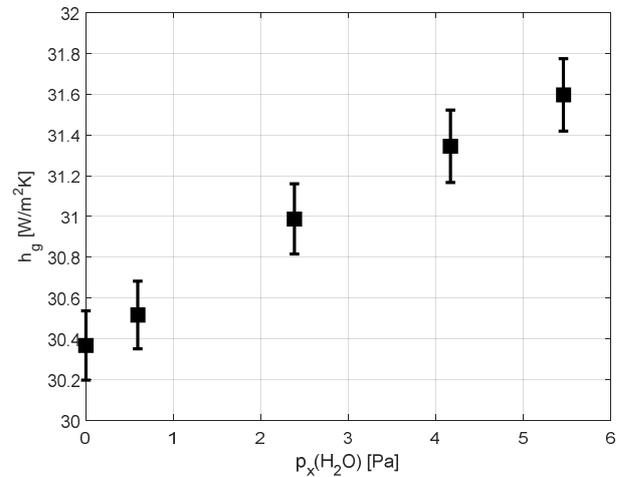
**Table 2** Change in  $\alpha_s$  after performing cleaning procedure on metal samples.

Sample	$\Delta\alpha_s$ [%]
A	-8.1 %
B	-12.4 %
C	0.5 %
D	-1.5 %
E	-4.1 %
F	-2.3 %

The previous investigation shows the vulnerability of the thermal accommodation coefficients to adsorbed monolayers on the surface and is in line with prior research [3], [4]. In order to investigate this in a more controlled manner, a pre-defined concentration of traces is added to the vacuum. This allows in-situ monitoring of a change in heat transfer coefficient due to monolayer formation. One example of such an experiment is depicted in Figure 5. Here subsequently 0.6 Pa, 2.4 Pa, 4.2 Pa, and 5.5 Pa of water is added to a 50 Pa total pressure of nitrogen. Measured impact of adding water on the heat transfer coefficient is up to 4.0 % compared to the case where no additional water is added.

Note that this not necessarily resembles a change in the thermal accommodation coefficient as adding water to the carrier gas also changes the overall gas properties. Moreover, it is very likely that this result is influenced by initial monolayers

of water being adsorbed on the sample surface while transporting from the vacuum bake-out facility towards the measurement setup. In order to examine this further, different trace gases and / or an in-situ water desorption facility needs to be realized.



**Figure 5.** Impact of adding water on heat transfer coefficient in gap using nitrogen as carrier gas. Error bars indicate  $\pm 1\sigma$  on measurement data.

### 4. Conclusions

An experimental setup is realized to measure the thermal accommodation coefficient in rarefied gas conditions. From this coefficient, the pressure dependent heat transfer between two solid surfaces can be calculated using the Sherman-Lees relation. The measurement reproducibility of the setup is shown to be in the order of  $1\%3\sigma$ . From the impact analysis on the cleaning procedure, it can be derived that it is crucial to apply a vacuum bake-out in applications where a predictable thermal accommodation coefficient is required. Future research will focus on gaining better physical understanding of the effect of surface cleanliness on the thermal accommodation coefficient.

### References

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