



Conductive heat transfer in a gas confined between two concentric spheres: From free-molecular to continuum flow regime



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ABSTRACT

The conductive heat transfer through a gas confined between two concentric spherical shells maintained at different temperatures is investigated from the free-molecular to the continuum flow regime. The heat flux, measured using a recently proposed experimental system to extract the thermal accommodation coefficient, is compared with analytical expressions and numerical results. From this comparison it is found that in the free-molecular flow limit, the experimental data are well explained by the analytical expression for the arbitrary radius and temperature ratios of the spherical surfaces. In the continuum limit, the temperature dependence of the thermal conductivity coefficient should be considered in the analytical expression. In the transitional flow regime, a revised function for the heat flux interpolation is proposed to give better fitting to the numerical results. By employing these knowledge, the thermal accommodation coefficient extraction procedure for the system is revised, and it is shown that the recalculated accommodation coefficient allows to reproduce well the measured heat flux.

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1. Introduction

The heat transfer through a rarefied gas confined between two surfaces with different temperatures is a fundamental issue which has been studied for a long time [1,2]. In parallel to the study of the theoretical aspects of the heat transfer as its dependence on the gas nature, composition and pressure various practical applications were found, such as the principle of operation of the Pirani sensor, which uses the dependence of heat flux on the pressure for the pressure measurements. Despite the long history of investigations of heat transfer between the two surfaces, there are several aspects which remain not very well known until now. One of these problems lies in the interaction of gas molecules with surfaces, which significantly affects the intensity of the heat transfer between the surfaces. This interaction may be explained in terms of thermal accommodation coefficient. The thermal or energy accommodation coefficient α is defined as [1,2],

$$\alpha = \frac{\bar{E}_i - \bar{E}_r}{\bar{E}_i - \bar{E}_s}, \quad (1)$$

where \bar{E} is the mean energy of the molecules colliding to a surface; the subscripts *i* and *r* correspond to the incident and reflected molecules, respectively, the subscript *s* corresponds to the molecules fully accommodated to the surface. This coefficient is useful in the analysis and the management of heat transfer in micro- and nano-devices, where gas flow should be treated as rarefied, even if the operating pressure is an atmospheric pressure, due to their small characteristic dimension. Additionally, the surface-to-volume ratio of the fluid for micro- and nano-devices becomes much larger than that for the conventional devices, therefore, the gas-surface interaction plays an essential role [3–8].

In this study, we focused on the heat transfer problem between two concentric spheres. This geometry was employed in a novel measurement system of the thermal accommodation coefficient, which characterizes the mean energy transfer through the gas-surface interaction [5]. This measurement system is based on the low pressure method, firstly introduced by Knudsen, later employed by many researchers [1]. This method employs the particular property of heat transfer at low pressure: the heat transfer between two surfaces maintained at different temperatures is proportional to the pressure between them and the thermal accommodation coefficient. Therefore, the heat flux through rarefied gas confined in concentric spherical shells is measured as a function of pressure, then the thermal accommodation coefficient is

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extracted. The novel measurement system is able to measure the thermal accommodation coefficient on non-metal surfaces, which is rarely reported in the literature due to specificity of the measurement methods [2,4], and it is especially important for micro- and nano-devices because of the materials employed.

Recently, the heat transfer between the two concentric spheres is also simulated [9] on the basis of the nonlinear S-model kinetic equation [10]. In the free-molecular, slip and continuum flow regimes, the analytical expressions are provided for arbitrary temperature and spheres' radius ratios. In the transitional regime, the S-model kinetic equation is solved numerically. Then, the limits of the applicability of the obtained analytical expressions and the previous empirical relation are established by confronting the numerical and analytical solutions.

The objective of this study is to evaluate the accuracy of the empirical heat flux expression between the free-molecular and continuum flow regime, and revise the expression valid for the whole range of the flow regime. The analytical heat flux expressions in the free-molecular and continuum flow regimes and the numerical data in the transitional flow regime, obtained in Ref. [9], are used to derive this revised heat flux expression. Then, based on the measurements of the heat flux and the pressure between two spherical shells, provided in Ref. [5], the values of the thermal accommodation coefficients are derived using proposed revised expression of the heat flux. Finally, the numerical simulations are carried out using the S-model kinetic equation with the obtained thermal accommodation coefficients, and the measured and simulated heat fluxes are compared to validate the revised expression.

2. Analysis of experimental heat flux data

The experimental data on the heat flux reported in Ref. [5] are analyzed in the following. The two concentric spherical shells configuration is chosen as the experimental setup to measure the thermal accommodation coefficient on non-metal surfaces. A tiny heater, maintained at temperature T_H by an analog electrical circuit, is fixed at the center of a spherical vacuum chamber. The tiny heater has a thin flat-plate shape, and the test sample surfaces are attached to the heater. The surface of the vacuum chamber made by Pyrex is maintained at the temperature T_C by immersing the chamber in a water bath. The inner radius of the chamber is equal to $R_C = 49.5$ mm. The heat flux from the tiny sample to the chamber surface is measured together with the pressure in the chamber. By using the expression relating the heat flux between the surfaces and the pressure, the thermal accommodation coefficient is derived. The configuration of the experimental setup is explained in detail in Ref. [5].

The heat flux from a heated surface surrounded by a monatomic gas in the free-molecular flow regime is expressed as,

$$q_{FM} = \frac{\alpha}{2} \bar{v} p (T_H - T_C), \quad \bar{v} = \sqrt{\frac{8kT}{\pi m}}, \quad (2)$$

here T , p and \bar{v} are the temperature, pressure, and mean molecular speed of the gas, respectively; k is the Boltzmann constant and m is the molecular mass of the gas. It is important to underline that the heat flux is proportional to the pressure of the gas and, therefore, to the gas number density. The heat flux between two surfaces maintained at different temperatures in the free-molecular flow regime, Eq. (2), is independent of the geometrical configuration of the system, see Refs. [4,3,9]. The accommodation coefficient α can be obtained by fitting heat fluxes measured as a function of pressure by Eq. (2).

However, it is difficult in a simple apparatus to maintain the free-molecular flow regime (*i.e.*, low pressure environment) owing to leakage. An alternative way is to build a high vacuum experi-

mental setup; however, in this case, the measurement system becomes huge and costly. In addition, it is also not easy to measure very small heat flux at low pressure environment. To realize the measurement in a low-cost simple apparatus, a much higher pressure condition is favorable for the measurement. A more general model for the heat flux through a gas from a heated surface has to be implemented for the accommodation coefficient extraction for this condition extended to the higher pressure. For the whole flow regimes, *i.e.* from the free-molecular to continuum flow regimes, the expression of the heat flux q can be approximated by a simple empirical interpolation of the free-molecular limit heat flux q_{FM} , Eq. (2), and the continuum limit heat flux, q_C , as it was done in Refs. [4,3,11,12], and it is expressed as

$$\frac{1}{q} = \frac{1}{q_{FM}} + \frac{1}{q_C}. \quad (3)$$

For the continuum limit the heat flux q_C is described by Fourier's law and it is independent of pressure and dependent upon the flow geometry. By making the size of the internal heated surface relatively small compared to the external surface of the vacuum chamber, the heat transfer problem is approximated by a simple spatially symmetric heat transfer between two concentric spherical shells, even though the shape of this internal heated surface is not a sphere but a flat plate, as mentioned above [5]. Following this model of two spherical shells, we can calculate the radius of the internal "virtual" sphere from the surface areas equality: the surface of the internal "virtual" sphere of a radius R_H has the same surface area as the real heated surface. From this equality, the radius of "virtual" internal sphere is estimated as $R_H = 4.95$ mm. Thus, the radius ratio of the concentric spherical shells, $\mathcal{R} = R_C/R_H$, is equal to 10 and it is relatively large. By assuming the concentric spherical shells geometry, the theoretical heat flux at the continuum limit q_C in Eq. (3) is expressed as

$$q_C = \kappa (T_H - T_C) \frac{R_C R_H}{R_C - R_H} \frac{1}{R_H^2}, \quad (4)$$

where κ is the thermal conductivity of the gas. The temperature inside the spherical vacuum chamber is assumed to be equal to the temperature of the surface of the external spherical shell T_C [5,4]. Therefore, in this analysis, the temperature dependence of the thermal conductivity κ along the radial direction is not taken into account, and the thermal conductivity at the temperature of the external spherical shell, T_C , is used for the entire region inside the vacuum chamber: $\kappa = \kappa(T_C)$. In addition, the pressure is assumed to be constant between the shells.

To minimize an error which can come from the use of the empirical relation, Eq. (3), the pressure condition is limited below 1.6 Pa in the experiment so that the measurement is realized in the near free-molecular regime.

In order to test this new developed experimental setup, first a platinum sample is used. A platinum foil with a thickness of 10 μm (Nilaco) is selected as a sample surface. Five values of the hot sphere surface temperature, T_H , are stated in the experiments, see Table 1. The cold sphere temperature, T_C , is almost the same for all five cases and equal to a room temperature. A number is attributed for each hot temperature value to simplify the reference. The averaged accommodation coefficients, extracted by the described above procedure from three measurements of the heat flux and pressure for each case, are provided in Table 1. Surface temperatures were different for each measurement, and the mean surface temperatures are listed, with any variation from the mean value less than 0.2 K. The relative standard errors of the accommodation coefficient did not exceed 1.6%, showing good repeatability of the measurements. However, it was not so simple to estimate the measurement accuracy of the system [5], and the number of significant

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