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NON-CLASSICAL HEAT TRANSFER EFFECTS IN MICROSCALES

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KEY WORDS

Nonequilibrium flows, kinetic method, Boltzmann equation, anomalous transport.

ABSTRACT

Introduction

Micro-scale flows are of great interest to modern industry and are highly susceptible to the interplay of a number of non-classical effects due to the fact that their scales are comparable to the local mean free path. These nonequilibrium flows are studied on the basis of Boltzmann equations or simplified kinetic equations using appropriate numerical methods capable of resolving such phenomena. Boundary conditions play an important role in the analysis of such flows: through the influence of accommodation coefficients, as well as through the influence of wall roughness or its relief [1].
Some interesting anomalous heat transfer effects for different classes of nonequilibrium flows have been analyzed using numerical solutions of kinetic equations [2-5]. Taking into account that the classical constitutive relations for shear stress and heat flux are approximations valid for almost equilibrium flows, it can be assumed that they can be broken in nonequilibrium flows under certain conditions. In this case, the H-theorem remains valid, so the second law of thermodynamics in the extended formulation is valid. Theoretical studies of non-classical effects may give a valuable view of their prospects for industrial application.

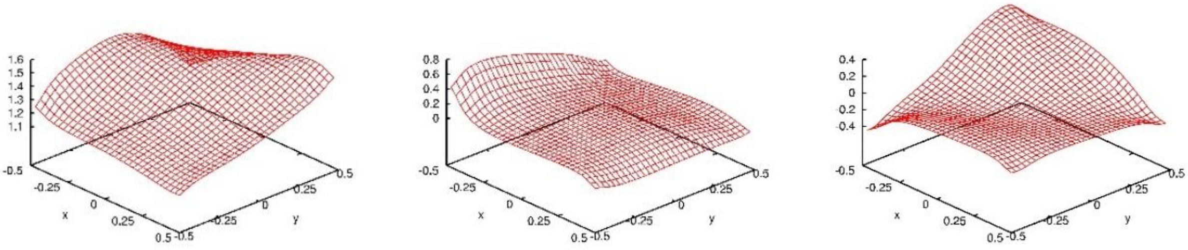
Methods and Problems under Consideration

In this paper we consider problems of interest for the study of non-classical thermal effects. For such problems, the solutions obtained by two methods are compared: the direct method for the Boltzmann equation [3] in the UFS version [6] and the direct Monte Carlo simulation (DSMC) method [7].
We study anomalous heat transfer in rarefied gas flows and try to classify different situations of occurrence of this phenomenon. For classification, in addition to numerical methods, some analytical approaches for qualitative and quantitative estimates are used. Namely, the expansion in powers of the small parameter (the inverse of the Mach number, different for each molecular velocity) in the nonuniform relaxation problems (NRP) in [2, 3]; the method of approximation of Liu and Lees in the problem of heat transfer with non-equilibrium boundary conditions; the Hermite polynomials expansion for NRP in the linear case [8]; the expansion in powers of the inverse Knudsen number near the free molecular flow for the membrane-like boundary conditions problem. The character of the asymptotic approximation near the equilibrium for NRP is studied as well. The conditions for realization of the anomalous transport effects in NRP are obtained in [9]. These analytical procedures confirm the anomalous effects.
Recently, the authors considered the problem of non-equilibrium heat transfer between plates. The results of

calculations by two methods for the case of ellipsoidal distribution function for reflected molecules with different ratios of longitudinal and transverse temperatures were presented. Interestingly, for Kn=1, the variable profiles show a positive temperature gradient across the whole region simultaneously with a positive heat flux.

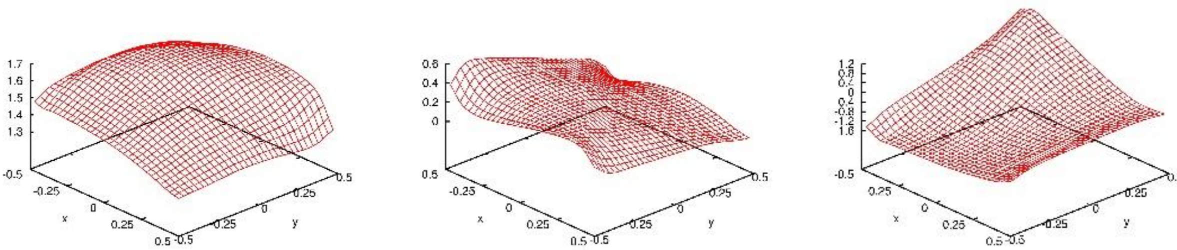
Results

In the present paper a main attention is paid to new formulations and solutions of one dimensional (1D) and two dimensional (2D) problems with the membrane-like boundary conditions. The boundary conditions are similar to the vapor-liquid boundary conditions [10], but new conditions with non-equilibrium distributions are considered. The cases of a full and partial permeability for 1D are considered and nonequilibrium flows in the region between membranes exhibit anomalous heat transfer properties.



T $\qquad$ q_x $\qquad$ q_y

Figure 1: Solutions of 2D problem with non-equilibrium boundary conditions. Distributions of the components of heat flux q_x and q_y, distribution of the temperature T (Kn=0.1).

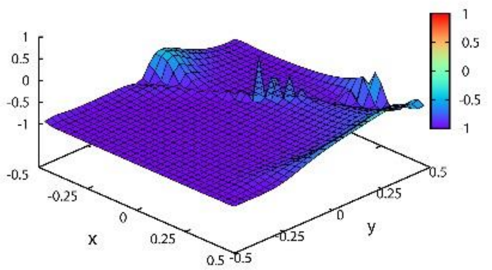


T $\qquad$ q_x $\qquad$ q_y

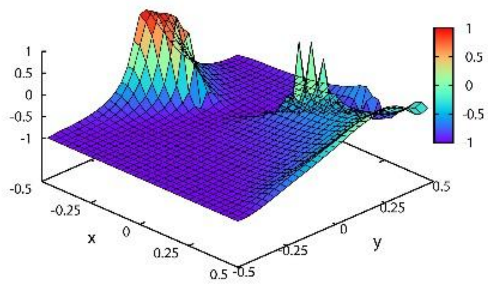
Figure 2: Solutions of 2D problem with non-equilibrium boundary conditions. Distributions of the components of heat flux q_x and q_y, distribution of the temperature T (Kn=10).

The case of full permeability for 2D problems is considered. The boundary conditions for the variant are superpositions of Maxwellians. Namely, boundary conditions are as follows. For square sides we have:
For the left boundary ($x = -0.5,\ -0.5 \le y \le 0.5$): $f = f_M(n,\ 1.6, 0, 1) + f_M(n,\ 0.4, 1)$, where $n = 0.1 - 0.09(y + 0.5)$;
For the right boundary ($x = 0.5$, $-0.5 \le y \le 0.5$): $f = f_M(0.1, -0.3, 0,\ 1) + f_M(0.1, -0.6, 0, 1)$;
For the top boundary ($-0.5 \le x \le 0.5$, $y = 0.5$): $f = f_M(n_1, 0, -1.2, 1) + f_M(n_1, 0, -0.4, 1)$, where $n_1 = 1 - 0.9(x + 0.5)$;
For the bottom boundary ($-0.5 \le x \le 0.5$, $y = -0.5$): $f = f_M(1,\ 0,\ 0.8,\ 1) + f_M(1, 0, 0.3,\ 1)$.
Here $f_M(n, u, T)$ denotes Maxwellian with density n, mean velocity u and temperature T.
A wide range of Knudsen numbers was studied for this problem: 0.025 < Kn < 10. Here Kn$=l/L$, where l is the mean free path and L is the length of the region under consideration. The distributions of the temperature and heat flux components are shown in Fig. 1, 2 for Kn=0.1 and Kn=10, respectively. Non-classical properties are observed in some parts of the domain for moderate and high Knudsen numbers. In Fig. 3 the cosine value of the angle between the heat flux and temperature gradient vectors is presented. Strictly

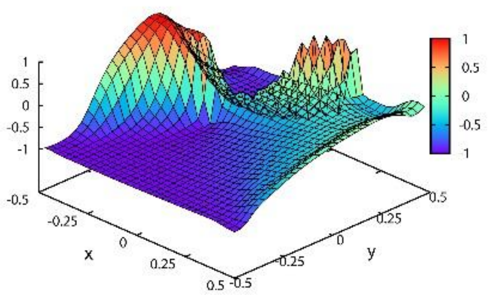
speaking, the Fourier relation can only be valid if cos(**q**, grad T) = -1. As can be seen, there are wide non-classical heat transfer zones for high and moderate Knudsen numbers. For smaller Knudsen numbers these zones are smaller, for Kn ≤ 0.1 there is already a very narrow region where cos(**q**, deg T) > -1.



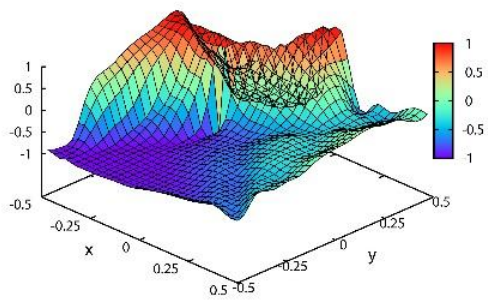
Kn=0.1



Kn=0.25



Kn=1



Kn=10

Figure 3: Solutions of 2D problem with non-equilibrium boundary conditions for different Knudsen numbers (Kn). Distributions of cos(**q**, grad *T*).

Summary and outlook

In this extended abstract we briefly describe results concerning anomalous heat transfer in certain non-equilibrium flows and present new results for effects in the two-dimensional problem.
As a generalization, one can consider non-equilibrium flows for mixtures with chemical reactions, which are of interest for some applications in regions of different shapes.
Possible experimental confirmations of the effects can be discussed. For NRP, the main practical task is to create and maintain a boundary non-equilibrium distribution. The new technology can be based on optical lattices [11], we simulated such processes in [4]. Other possibilities of creating such effects are as follows: a magnetic trap [12]; an oscillating plate; molecules emitted from a surface with a non-equilibrium distribution function [13]. Non-equilibrium flows can be formed in the region between the boundaries with equilibrium distributions, for example, for particles entering the region through thin membranes [14]. The main question concerns the validity of these hypothetical boundary conditions. With the development of microtreatment technology, membranes of mixed cellulose esters (MCE) with a pore size of 100 Nm are introduced (see, for example, [15]), i.e. the Knudsen number in the pore $Kn_p \sim 1$ at atmospheric pressure.
From the consideration of the flows in the lid-driven cavity it can be concluded that in such configurations there are also different physical situations with anomalous heat transfer [16]. Experimental confirmations of the discussed effects allow presenting the prospects for the creation of new microdevices without mechanical parts, as for the effect of thermal transpiration, which is the basis of Knudsen pumps. One can suppose that anomalous thermal effects can be realized in new microdevices. In particular, micro-refrigerators are very important, especially in electronics, some new approaches can be proposed for them.

Natural examples of anomalous transport properties can also be discussed. Under normal conditions, a spontaneous non-equilibrium state relaxes to equilibrium in a very short time. But such phenomena can be observed in nature at non-equilibrium conditions: in the wakes of high-speed objects (meteors, rockets), in astrophysical systems, and possibly in biological objects.

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