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Technical Note

Critical view on "new results in micro-fluid mechanics": an example

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Abstract

Experiments in micro-flow devices almost always show deviations compared to the corresponding situations in macro-systems. Often special "micro-effects" are proposed to explain these unexpected results. However, based on a nondimensional form of the problem formulation these "micro-effects" can be identified as scaling effects referred to a standard analysis in macro-dimensions. Thus many "unexpected results" can be explained. This is demonstrated for a specific example recently published in this journal.

1. Introduction

Collecting results from experiments in micro-flow devices one might get the impression everything is new and surprising. This impression is supported by statements in review articles like:

> "...the unique features in micro-mechanics are perhaps the most intriguing ones for researchers in basic fluid mechanics [1]."

> "...More research is needed in this relatively new and exciting field [2]."

A specific example, published recently in International Journal of Heat and Mass Transfer [3] may illustrate this and—at the same time—may serve as an example to show that a critical view might help to avoid misleading conclusions.

In [3] laminar pipe flow under the thermal boundary condition of constant wall heat flux density is investigated experimentally. For this standard situation the Nusselt number is $Nu = \dot{q}_W D/[\lambda(T_W - T_B)] = 4.36$ when the flow is fully developed, at least that is what can be found in heat transfer textbooks. For small Reynolds numbers the fully developed flow is reached after a few diameters downstream. Though the flow under consideration in [3] undoubtedly is fully developed for most parts of the test section measured Nusselt numbers are far away from a constant number 4.36. In Fig. 1 some details of the test section as well as the main results are shown. Nusselt numbers are between 1 and 2 for the Reynolds number $Re \approx 50$ of this example and depend on the Reynolds number (not shown here). It is important to mention that the bulk temperature T_B could not be measured inside the pipe but was interpolated between the inlet and outlet temperatures that were measured. From their understanding of the physics of the problem the authors assumed a linear interpolation to be adequate. The authors' explanation for this unusual behaviour are dissipation effects in the narrow pipes. Since, however, Eckert numbers in this case are of the order of $Ec = 10^{-9}$ and dissipation effects can be neglected in the limit $Ec \to 0$ they claim *variations* of the Eckert number to be responsible for the unexpected heat transfer behaviour. They call these effects "secondary Brinkman effects" since they use the Brinkman number $Br = EcPr$ rather than the Eckert number itself (Pr is the Prandtl number, an O(1) quantity).

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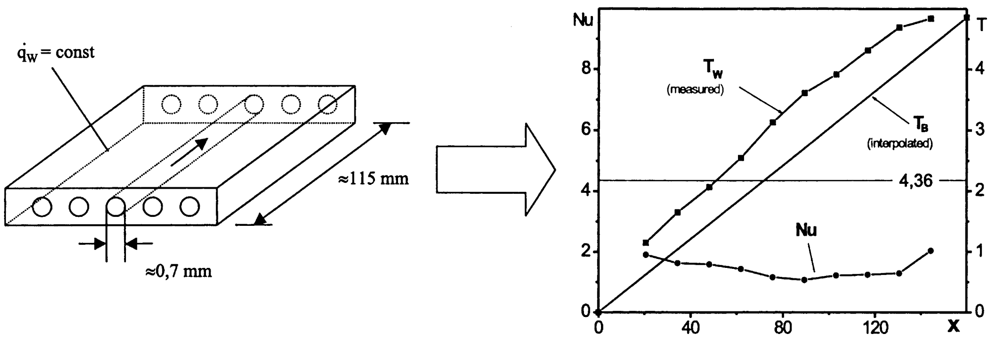

Fig. 1. Laminar pipe flow under constant wall heat flux density; published in [3]; $Re = u_m D_h/\nu \approx 50$.

2. Dimensional analysis and scaling effects

In a common definition flows in devices with characteristic dimensions of less than 1 mm are called flows in micro-devices. Often MFD is introduced for "micro-flow devices". Flows in devices of ≈1 mm in size undoubtedly are still continuum flows described by the Navier–Stokes equations if the fluid is Newtonian. Reducing the characteristic lengths from 1 mm = 1000 μm to lengths of the order of 1 μm($= 10^{-6}$ m = 1 micron) may give a new situation. For gases with a mean free path of the molecules of 5×10^{-8} m = 0.05 μm one might no longer be in the continuum range and the Navier–Stokes equations are no longer adequate.

However, assuming devices with dimensions >5 μm (corresponding to Knudsen numbers $Kn < 10^{-2}$ for gases) one is well in the range of continuum theory. For liquids with a distance between the molecules much smaller than that for gases of course there also is continuum flow with geometric lengths >5 μm.

Excluding slip flow as well as free molecule flow by assuming devices of adequate size (>5 μm) there is a common theoretical basis for macro- and micro-flows: the Navier–Stokes equations (assuming Newtonian fluids). In a nondimensional version all problems are characterised by geometries with dimensions of order one and categories like "macro" or "micro" do not exist. Nevertheless certain effects can be of different importance in micro- compared to macro-systems. This situation can best be described by introducing the terms "standard macro-analysis" and "scaling effects with respect to standard macro-analysis". These terms stem from dimensional analysis considerations. Here "standard macro-analysis" means an analysis that neglects all effects that are of minor importance in macro-dimensions. These effects may, however, become important in micro systems and then are called "scaling effects with respect to a standard macro-analysis".

Based on these considerations the following scaling effects in micro-flow devices can be identified (for details see [4]):

(1) Axial heat conduction (small Peclet numbers).
(2) Conjugate heat transfer (relatively thick walls).
(3) Temperature dependent properties (large axial temperature gradients).
(4) Pressure dependent properties (large axial pressure gradients).
(5) Wall roughness (specific wall roughness distribution).

With a critical view on the experimental set-up in [3] the first two of these scaling effects may be identified as crucial. Thus taking into account axial heat conduction as well as conjugate effects should explain Tso and Mahulikar's results in a conventional manner (with no need to have recourse to special micro-effects). An easy way to do this is by a numerical approach to the problem.

3. Accounting for scaling effects

Since the micro-pipes of the study in [3] are relatively short (≈150 D_h) variable property effects due to axial temperature and pressure drops probably are of minor importance. We therefore first concentrate on axial heat conduction and conjugate effects. CFD calculations with adequate grid resolution are a proper tool, since the flow is laminar so that there is no turbulence modelling problem and even in combination with heat conduction in the solid walls the overall approach is that of a direct simulation. Based on the CFD code CFX 4.3 by AEA technology we calculated the conjugate problem with the flow and thermal boundary conditions of the experiments in [3]. The main results are given in Fig. 2. Compared to Fig. 1 (experimental results) it turns out that the bulk temperature T_B is not at all linearly distributed between the inlet and outlet values. Physically this corresponds to strong conjugate effects and considerable axial heat conduction.

The Nusselt number evaluated with the actual temperature difference $T_W - T_B$ in the central part of the

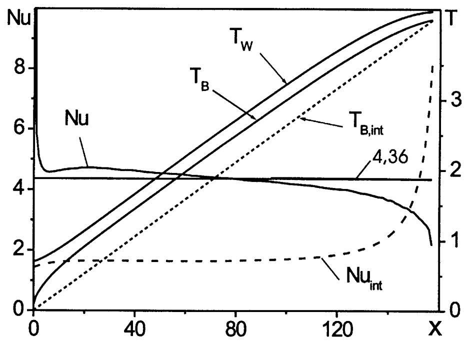

Fig. 2. Calculated heat transfer results (see Fig. 1) (– – –) temperature and Nusselt number distributions for a lineary interpolated bulk temperature.

pipe is very close to $Nu = 4.36$, the standard value for fully developed heat transfer with $\dot{q}_W = \text{const}$.

With an interpolated bulk temperature, called $T_{B,int}$ in Fig. 2, however, a totally different Nusselt number distribution Nu_{int} appears. This one is very close to the Nusselt number distribution in Fig. 1.

4. Final remark

Though the example given in this paper is a single phase convective heat transfer problem our general hypothesis is by no means restricted to this physical situation. The basic idea, that, starting from a common theoretical background adequate models can be identified for different orders of scales (and that scaling effects refer to specific models) is not even restricted to the Navier–Stokes equations as a common basis. Therefore, whatever is usually found to be "a special micro-effect" may be interpreted as a "general effect that may be neglected in most or all other orders of scaling dimensions".

Though this seems to be basically the same fact just seen from a different perspective the advantage is that it stimulates a more systematic approach to problems in unfamiliar scales.

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