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Experimental analysis of the influence of wall axial conduction on gas-to-gas micro heat exchanger effectiveness

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ABSTRACT

In this paper an experimental investigation of the thermal performances of gas-to-gas micro heat exchangers operating under different flow configurations (co-current, counter-current, cross flow) is presented and the results are compared with the predictions of the conventional correlations developed for the design of the conventional-sized heat exchangers. A double-layered microchannel heat exchanger has been specifically designed in order to be able to reproduce co-current, counter-current and cross flow gas arrangements. The core is housed in a shell made of polymer; on the contrary, the foil between the hot and cold flow is exchangeable; several foils made with different materials (copper, peek, stainless steel and aluminum) and with different thickness have been investigated in order to put in evidence the effect due to the axial wall-fluid conjugate heat transfer on the thermal efficiency of the micro heat exchanger. The results show that the conjugate heat transfer can be very strong in micro heat exchangers and it tends to reduce the effectiveness of counter-current micro heat exchangers and to increase the effectiveness of cross flow micro heat exchangers. In the case of a co-current arrangement with balanced flows the role of the wall axial conduction can be considered negligible.

1. Introduction

Recent development in miniaturization technologies has facilitated the downsizing of conventional heat exchangers to micro-scale in order to achieve energy-efficient devices which have very large ratios of heat transfer surface to flow volume. Even though the hydraulic diameter of the flow passages in micro heat exchangers can be greatly reduced thanks to microfabrication technologies, the partition walls between the flow passages cannot be excessively thin in order to maintain an adequate mechanical strength. This mechanical constraint makes thicker the partition walls of the micro heat exchangers if compared with the hydraulic diameters of their channels with respect to their conventional counterparts. This physical feature may results in strong wall-fluid conjugate heat transfer effects which influence the thermal performance of micro heat exchangers, especially if the partition walls are made of solid material with a large thermal conductivity.

For this reason, while the problem of wall axial conduction remains of secondary importance in conventional heat exchangers, its influence on the thermal performance of the micro heat exchangers must be accurately checked. The influence of wall axial conduction on the thermal performance of micro heat exchangers has been studied by a number of researchers in the past. Peterson [1] numerically examined the conjugate effects in microchannels and suggested to use material of very low thermal conductivity in the construction of counter-current micro heat exchangers in order to avoid strong axial conduction across the partition wall. Stief et al. [2] determined numerically the optimal value of the thermal conductivity of the walls of a micro heat exchanger in order to obtain the maximum value of the thermal efficiency; they demonstrated that for counter-current flow configuration the best performance cannot be reached if materials having very large thermal conductivity are selected, due to the increased weight of conjugate effects. This result has been confirmed recently by Moreno et al. [3] observing that highly thermally conductive material tends to decrease the thermal efficiency of micro heat exchangers. Hung et al. [4] showed numerically that the fluid experiences larger temperature change if the substrate of the micro heat exchanger is made of material with lower thermal conductivity. Koyama and Asako [5] demonstrated numerically that the reduction of the partition wall thickness among the hot and the cold flow allows to achieve higher thermal performance of gas-to-gas micro heat

Abbreviations: NTU, number of transfer unit; PEEK, polyether ether ketone.

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Nomenclature

A	heat transfer area (m^2)
c_p	gas specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
d_h	hydraulic diameter (μm)
F	correction factor
H	height of microchannel (μm)
k	thermal conductivity ($W\,K^{-1}\,m^{-1}$)
L	length of microchannel (mm)
$\dot{m}$	mass flow rate (kg/s)
p	pressure (Pa)
P	dimensionless temperature change defined by Eq. (19) (–)
Q	heat transfer rate (W)
Re	Reynolds number (–)
s_1	thickness of channel side-wall (μm)
T	temperature (K)
U	overall heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
W	width of microchannel (μm)

Greek symbols

ε	heat exchanger effectiveness (–)
ϕ	heat flux ($W\,m^{-2}$)
λ	axial conduction parameter (–)
μ	dynamic viscosity (kg/m s)

Subscripts

ave	average value
c	cold flow
f	fluid
h	hot flow
in	inlet value
out	outlet value
w	wall

exchangers by reducing the conjugate effects between the solid wall and the fluids.

From an experimental point of view, in the case of liquid micro heat exchangers many works published in the past did not report whether axial conduction plays a role in the thermal efficiency of the devices [6–9]. On the contrary, in the experimental tests of gas micro heat exchangers the influence of axial conduction has always been recognized as crucial for the optimization of the thermal performance of these devices. One of the first works on experimental analysis of gas-to-gas micro heat exchangers was done by Bier et al. [10], who found that gas micro heat exchangers works like a temperature mixer between cold and hot flows if an highly conductive partition wall is present. Meschke et al. [11] evidenced experimentally lower values of the heat transfer coefficient with respect to the theoretical predictions based on conventional theory in a ceramic gas micro heat exchanger and they explained these reduced values by invoking the strong axial conjugate effects across the thick solid walls of their device. Similar conclusion was drawn by Koyama and Asako [12] by conducting a series of experiments with stainless steel gas micro heat exchangers. In this work no significant difference in terms of thermal performance was found between co-current and counter-current flow arrangement and the main conclusion of the researchers was that the flow configuration has a negligible influence on the efficiency of gas micro heat exchangers if strong conjugate effects are present.

This short review of the published work on gas micro heat exchangers puts in evidence how many researchers found that the thermal performance of these devices is degraded by the presence of a significant axial conduction across the partition walls. However, the results reported in these works are not sufficient in order to have a deeper systematic insight into the influence of axial conduction on the performance of gas micro heat exchangers because the experimental conditions vary from one work to another but are far to cover all the cases of interest. The main aim of this paper is to fill this gap by means of a parametric experimental analysis of the influence of the conjugate heat transfer on the performance of gas micro heat exchangers using a specific double-layered microchannel heat exchanger presented by the same authors in [13]. The hot and cold layers of the micro heat exchanger are manufactured into polished PEEK material with large thermal resistance in order to minimize the heat losses. The layers can be rotated in order to transform the heat exchanger in cross flow or counter current flow or parallel flow configuration. The partition foil between the two layers is designed to be exchangeable; in this way it becomes possible to test different partition foils made with different materials and thicknesses, allowing for comparative study of the influence of axial conduction on thermal performance. In this way the role of the axial conduction across the partition foil has been experimentally investigated for different flow configurations and the results have been compared with the predictions of the correlations developed for the design of conventional-sized heat exchangers [14,15].

2. Experimental set-up

The schematic layout of the experimental test rig used in this work is shown in Fig. 1: pressured air flow at room temperature is supplied by the gas source (1 in Fig. 1) with a pressure up to 40 bar. The gas flow is firstly filtered by a 60 μm filter (2, *Swagelok*) to get rid of possible impurities. The flow is split (3, 4 *Swagelok*) into two branches in order to feed the hot and cold branch of the micro heat exchanger (7). The flow rate of each branch is controlled by means of a mass flow controller (5, *Brooks SLA5851 or SLA5853*). The gas mass flow rate is regulated between 0.5 and 3.0 kg/h in order to generate the same mass flow rate between the hot and the cold branches (balanced flows); the relative difference in terms of mass flow rate between the two flow branches remains smaller than 1% throughout all the tests. The gas temperature is controlled by using a temperature unit (6) to provide both hot and cold flows at required temperature. The hot and the cold gases flow through the micro heat exchanger and finally they are vented to the atmosphere.

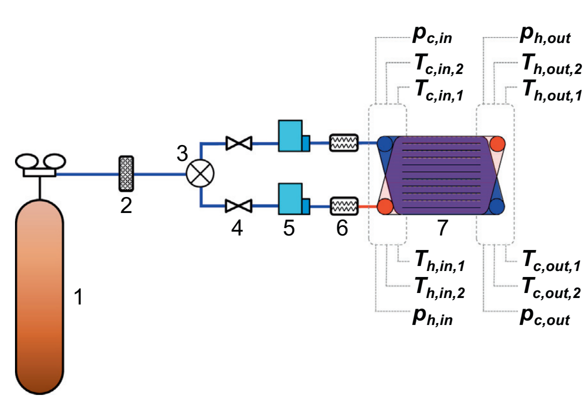

Fig. 1. Layout of the test rig. (1 – Gas source, 2 – filter, 3 – flow splitter, 4 – valves, 5 – mass flow controller, 6 – temperature regulator, 7 – micro heat exchanger).