Applied Thermal Engineering 40 (2012) 236–247

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Degradation of the performance of microchannel heat exchangers due to flow maldistribution

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ARTICLE INFO

Article history:
Received 16 August 2011
Accepted 9 February 2012
Available online 17 February 2012

Keywords:
Microchannels
Flow maldistribution
Thermal cross talk
Parallel plates

ABSTRACT

The effect of flow maldistribution on the performance of microchannel parallel plate heat exchangers is investigated using an established single blow numerical model and cyclic steady-state regenerator experiments. It is found that as the variation of the individual channel thickness in a particular stack (heat exchanger) increases the actual performance of the heat exchanger decreases significantly, deviating from the expected nominal performance. We show that this is due to both the varying fluid flow velocities in each individual channel and the thermal cross talk between the channels transverse to the direction of the flow.

1. Introduction

Microchannel heat exchangers show promise of theoretically large heat transfer coefficients and provide the ability to design compact devices. These are two very central parameters in the areas of, e.g., cryocoolers, dehumidifiers, Stirling engines, solar power, electronics cooling and magnetic refrigeration [1–7].

Parallel plate heat exchangers are considered, from a theoretical standpoint, to have a good ratio between heat transfer properties and pressure drop. In order to reach sufficient values of the number of transfer units (*NTU*) and heat transfer coefficient, h, the flow channels defined by the parallel plates, or similar geometries, must be made into the sub-millimeter regime. This is due to the fact that, assuming a constant Nusselt number, the only parameter that can increase h is a decrease in the hydraulic diameter, d_h. The required flow rate, specified through operating frequency and thermal utilization of the heat exchanger, defines a minimum value of h and thus d_h for a given value of the *NTU*. In many applications it is therefore important to have quite small channels (hydraulic diameters down to or even below 100 μm are not unrealistic for many applications) [8].

The range of hydraulic diameters from 1 μm to 1 mm is commonly defined as microchannels [9]. Significant discrepancies are, however, often observed between experiments and theory in this range. This has led to a quite significant amount of research into various aspects of the governing physics at the relevant scales.

1.1. Relevant physical effects at the microscale level

Several explanations for the relatively large deviations of the predicted heat transfer performance and that experimentally observed on the microscale have been suggested. These include physical effects not previously considered such as, e.g., whether the continuum assumption breaks down, the influence of surface roughness in the channels etc. In Ref. [9] these issues are reviewed and it is concluded that for incompressible laminar flows with aqueous fluids no new physical phenomena happen in microchannels. This is supported by careful experiments performed on single channel tubes and square channel heat exchangers in the microchannel range [9–11].

A range of assumptions are usually made in order to model the coupled fluid flow and heat transfer problem in heat exchangers in general. These issues are discussed in great detail in [9] and references therein. Here, they are summarized:

- Entrance effects
- Temperature dependent properties
- Viscous dissipation
- Surface roughness

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1359-4311/$ – see front matter
doi:10.1016/j.applthermaleng.2012.02.019

- Conjugate heat transfer
- Uneven flow distribution in flow manifolds

The entrance effects cover both hydrodynamic and thermal issues. It is important to investigate whether the flow may be considered fully developed and, in the case of a 1D model, also whether the thermal entrance length is relatively short.

Temperature dependent properties may influence the performance in several ways. If the viscosity of the heat transfer fluid varies significantly then the pressure drop in an actual experiment may be somewhat different than predicted. Similarly, if the specific heat and the mass density are sensitive to temperature then that may cause substantial deviations between the results observed experimentally and those predicted by a numerical model neglecting these effects.

The viscous dissipation is the irreversible conversion of mechanical energy to heat in the fluid due to the pressure drop. If this effect is considerable and not taken into account in a numerical model, then the heat transfer will be incorrectly predicted. A general criterion for estimating the importance of viscous dissipation is to calculate the pressure drop and use that to find the associated energy release. Comparing this number to the total amount of transferred heat in the system is a good estimate of the possible importance of the viscous heating.

The surface roughness is indeed difficult to model precisely. Several investigations have shown, however, that the impact of surface roughness on the heat transfer effectiveness may be either positive or negative depending on the characteristics of the roughness [12–14]. It is generally concluded that surface roughness increases the pressure drop [9].

The issue of conjugate heat transfer is the effect of thermal conduction in the flow direction in the heat exchanger solid. For small Reynolds numbers this effect may be quite significant and using simple Nusselt–Reynolds correlations may not sufficiently describe the actual heat transfer [9,11,15].

Finally, in a microchannel heat exchanger with multiple channels, flow maldistribution in the channels can be significant. If the channels are nominally small their spacing may be manufactured with a relatively large uncertainty. The resulting performance of the heat exchanger is difficult or even impossible to predict without the help of a numerical model resolving the heat transfer problem in at least two dimensions.

While much research on heat transfer and fluid flow modeling in microchannels generally studies a single channel [16,17], entire microchannel heat exchangers with practical manufacturing tolerances have received less attention. How fluid maldistribution in microchannel manifolds affects heat transfer performance was studied using a 3D model [18]. A 1D heat exchanger model was used to predict how flow maldistribution affects vapor compression system performance [19,20]. This method predicts that two individual plate stacks with different spacing will have poorer heat transfer performance than an equivalent stack with average plate spacing of the two. The performance of heterogeneous beds was estimated in various limiting cases for bundled parallel capillaries in Ref. [21]. Here, it was concluded that the effect of size variations of the capillary diameter generally reduces the performance. Flow and temperature distribution in parallel channels were studied numerically when obstructions such as bubbles or debris were placed in one of the channels [22]. The outlet temperature profile was shown to be affected by obstruction in one of the channels, but the change in heat transfer performance was not quantified.

However, the parallel heat exchanger approach cannot capture the effect of thermal interactions (cross talk) between adjacent fluid channels with different channel heights. The effect of this so-called cross talk on microchannel stack performance is not well understood.

In this paper we investigate the influence of flow maldistribution and the associated conjugate heat transfer using the 2-dimensional heat transfer and fluid flow model presented in Ref. [23,24] on four custom made parallel plate heat exchanger stacks built from commercial aluminum sheets. The four stacks all have the same plate thickness of 0.4 mm and number of plates but different nominal plate spacings ranging from 0.1 to 0.7 mm. The performance as passive thermal regenerators is investigated experimentally in a setup that allows a periodic flow in the system, and the performance is evaluated at cyclic steady-state.

The numerical model simulates a single blow process in a given inhomogeneous stack of parallel plates. The single blow technique is commonly used experimentally to determine heat transfer coefficients in difficult heat exchanger geometries such as packed beds. In this work the technique is performed numerically to assess the bulk heat transfer in a flat plate regenerator with inhomogeneous plate spacing. The reduction in heat transfer coefficient due to the inhomogeneity of the stack is determined through comparison with the ideal single channel case (which is completely equivalent to a homogeneous stack of any number of plates). This reduction factor is found at varying flow rates in order to probe the influence of flow maldistribution as a function of Reynolds number.

The four regenerators are tested under various operating conditions in the test device described below. The regenerators are subjected to a periodic fluid flow and a cyclic steady-state temperature span is thus achieved. A larger temperature span implies a larger heat transfer coefficient when comparing different stacks under otherwise the same conditions. In this way the model and experimental results may be compared in terms of the trends predicted by the two approaches, respectively.

2. Experimental

2.1. Construction of aluminum regenerators

The flat plate stacks were fabricated from 0.4 mm thick commercial grade Al plates that were laser cut to the dimensions 40×25 mm^2. Thin wires were used as spacers to regulate the plate spacing. Each stack was made with two wires sandwiched between each plate in a simple rig to facilitate easy plate stacking. After all the plates were stacked, the stack was compressed slightly to reduce the effects of slight bending of the wires and the plates were bonded with epoxy on both sides along the entire length of the plates in the flow direction (40 mm). The stacks were placed in nylon housings and sealed around the periphery of the stack with silicone to prevent heat transfer fluid from bypassing the stack. The fabrication and test procedure for the stacks is discussed in more detail in Ref. [25,26].

A Vantage Laser Scanner was used to scan the cross sections at both ends (fluid inlet and outlet) of each stack. The resolution along the direction of the stacking of the aluminum plates was set to 5 μm and along the transverse direction it was set to 20 μm (the *yz*-plane in Fig. 1). The laser scanner is designed to measure surface topology. However, in this case the data from the scanner was truncated to two values; one representing solid aluminum, the other representing void space, i.e. flow channels. In this way the channel and plate thicknesses were found through analyzing the 2-dimensional maps of the cross section at either ends of the stacks. The processed maps of each stack configuration are shown in Fig. A.12 in Appendix A. Arbitrarily the two cross sections for each stack are denoted “face 1” and “face 2”, respectively.