Available online at www.sciencedirect.com

SCIENCE DIRECT®

Experimental Thermal and Fluid Science 30 (2006) 801–809

Experimental Thermal and Fluid Science

www.elsevier.com/locate/etfs

Concepts and realization of microstructure heat exchangers for enhanced heat transfer

J.J. Brandner *, E. Anurjew, L. Bohn, E. Hansjosten, T. Henning, U. Schygulla, A. Wenka, K. Schubert

Forschungszentrum Karlsruhe, Institute for Micro Process Engineering IMVT, P.O. Box 3640, DE-76021 Karlsruhe, Germany

Abstract

Microstructure heat exchangers have unique properties that make them useful for numerous scientific and industrial applications. The power transferred per unit volume is mainly a function of the distance between heat source and heat sink—the smaller this distance, the better the heat transfer. Another parameter governing for the heat transfer is the lateral characteristic dimension of the heat transfer structure; in the case of microchannels, this is the hydraulic diameter. Decreasing this characteristic dimension into the range of several 10s of micrometers leads to very high values for the heat transfer rate.

Another possible way of increasing the heat transfer rate of a heat exchanger is changing the flow regime. Microchannel devices usually operate within the laminar flow regime. By changing from microchannels to three dimensional structures, or to planar geometries with microcolumn arrays, a significant increase of the heat transfer rate can be achieved.

Microheat exchangers in the form of both microchannel devices (with different hydraulic diameters) and microcolumn array devices (with different microcolumn layouts) are presented and compared. Electrically heated microchannel devices are presented, and industrial applications are briefly described.

Keywords: Heat transfer; Microstructure; Heat transfer efficiency; Pressure drop; Heat transfer enhancement

1. Introduction

Heat exchangers are devices conducting one of the most important unit operations in process engineering. A multitude of different designs has been realized in conventional macroscale technology.

The principles of heat exchanger design have been transferred to microscale devices, resulting in basic designs comparable to those known from macroscale devices, such as crossflow or counterflow heat exchangers, but providing much smaller characteristic dimensions [1,2]. The most important of these dimensions are the typical distance D between heat sink and heat source, and a characteristic lateral dimension. In the case of microchannel heat exchangers, which have been the dominating type to date, this characteristic lateral dimension is the hydraulic diameter d_h.

Since in the scaling-down from macro to microscale, the volume decreases with the third power of characteristic device linear dimensions, while surface areas only decrease with the second power, microstructure heat exchangers provide very high surface-to-volume ratios. Values of 30,000 m^2/m^3 and more have been reported [1,2].

For some special applications, like the nearly isothermal conduction of highly exothermal or endothermal reactions, or the heating or cooling of fluid streams with high temperature gradients at high mass fluxes, but at the same time with small pressure gradients, it may be necessary to enhance the heat transfer rates even more. The trade-off between heat transfer rates and pressure drop (pumping energy loss) is a central problem in the development of microstructure heat exchangers.

* Corresponding author. Tel.: +49 7247 823963; fax: +49 7247 823186.
E-mail address: juergen.brandner@imvt.fzk.de (J.J. Brandner).

0894-1777/$ - see front matter © 2006 Elsevier Inc. All rights reserved.
doi:10.1016/j.expthermflusci.2006.03.009

Nomenclature

Latin symbols

A	cross-section area, m^2
c	heat capacity, J kg^{-1} K^{-1}
C	circumference, m
d	diameter, m
D	distance, m
l	length, m
m	mass, kg
N	number, 1
T	(absolute) temperature, K
p	pressure, Pa
P	power, W
Q	heat, J
$\dot{Q}$	thermal power, W
x	longitudinal spatial coordinate, m
y	lateral spatial coordinate, m

Greek symbols

ε	heat transfer efficiency, 1
η	(dynamic) viscosity, kg m^{-1} s^{-1}
ϱ	density, kg m^{-3}
ϑ	temperature, °C

Subscripts

ch	microchannel(s)
cold	passage 1 (cold-in)
h	hydraulic
hot	passage 2 (hot-in)
in	inlet
out	outlet
p	at constant pressure
pump	pumping (ideal pumps, both passages)

Heat transfer enhancement methods have been reported earlier [3–5]. One possibility is the integration of micro or even nanostructured layers [6]. Another viable method is changing the internal microstructure layout from microchannels to more complex, and possibly three-dimensional flow path shapes.

In the following, various microstructure heat exchangers are presented and compared. First, several microchannel devices with different hydraulic diameters d_h will be compared with respect to their heat transfer capabilities. Second, two devices in which the microchannels have been replaced by different two-dimensional arrays of columnar microfins will be compared to each other and to a microchannel device with respect to heat transfer capabilities, which is related to the pressure drop across the device (pumping power loss). Finally, devices for scientific and industrial applications will be presented, and their use described briefly.

2. Microstructure heat exchangers

Microstructure heat exchangers are working according to the same principles as conventional (macroscale) heat exchangers. Microscale devices are nowadays available as commercial-off-the-shelf components from a number of vendors, in a variety of basic designs (crossflow, counterflow and concurrentflow), and suited to mass flows ranging from some milligrams per hour to several tons per hour, dependent on the sizes of the device as a whole and on the size of the integrated microstructures [1,2,7,8].

The manufacturing of microstructure heat exchangers has previously been described in details [1,9,10]. In Fig. 1, a crossflow microstructure heat exchanger made by mechanical micromachining of stainless steel foils, their subsequent stacking, diffusion bonding, and packaging, is shown.

2.1. Experimental details

Measurement results presented in the following were obtained on a microheat exchanger test rig described earlier [9,11], using deionized water as test fluid in both passages.

In the calculation of the power P_{pump} needed to force the fluid flows against the pressure drops in both passages, the finite efficiency of real pumps was neglected.

Standard measurement uncertainties of 0.5 K for the temperature measurements, 1% for the pressure measurements and 5% for the mass flow measurements were propagated in the determination of measurement uncertainties according to the GUM [12].

2.2. Microchannel heat exchangers

Microchannel heat exchangers are built by creating planar arrays of microchannels, e.g. by micromachining of

Fig. 1. Crossflow microstructure heat exchanger made of stainless steel. The manufacturing process is described in [1].