

A CROSS FLOW MICRO HEAT EXCHANGER DESIGN

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Abstract: Microfabrication techniques and scale-up by replication have fueled spectacular advances in the electronics industry and more recently in microanalysis chips for chemical and biological applications. Microfabrication also raises new opportunities for applications of the reaction engineering toolbox. The cross flow micro heat exchanger can transfer more heat/volume or mass than existing heat exchangers within the context of the design constraints specified.

Keywords: heat transfer, micro, heat exchanger

1. INTRODUCTION

Microfabricated devices, such as micropumps, microsensors, and microactuators, are called micro electro mechanical systems (MEMS). Recently, MEMS have accelerated advances in micro total analysis systems (μ TAS). The key technologies of μ TAS are microanalysis chips for chemical and biological applications such as DNA decoding equipment and on-site environmental monitoring systems. Miniaturization of chemical analytic devices reduces the amount of samples and cuts down the analysis time.

The characteristics of micro chemical plants are as follows:

- the ratio of surface area to volume is very high;
- the effective volume inside microdevices is very small;
- the fluid flow is laminar, and so on.

Analysis of chemical reactions and transport phenomena in microchannels has been performed energetically. In order to use microfabricated devices for production of fine chemicals, the technologies of design, operation, and control of micro chemical plants need to be systematized on the basis of the results of fundamental research [3].

In order to design the cross flow micro heat exchanger, performance criteria were established. Due to the similarity of design, a car radiator was selected as the application. The performance criteria may be slightly different for other applications such as air conditioning and aerospace, but the majority of principles that will be discussed can be extended to other applications.

2. MICRO HEAT EXCHANGER DESIGN

Compared with conventional heat exchangers, the main advantage of micro heat exchangers is their high heat transfer area per unit volume and hence the high overall heat transfer coefficient per unit volume. Micro channel heat exchangers are most common type of micro heat exchangers and generally consist of many channels fabricated from thin foils of silicon or metallic materials.

Typical cross-flow micro heat exchanger geometries use stacked micro channel plates alternating at 90°C. A disadvantage of the staking method is the cost and the time involved in manufacturing and bonding together the numerous plates. Fluids with similar properties are typically used as the heat transfer media and this allows

identical stacked plates to be used, making the fabrication process less complicated. As the channels on both sides are of the same geometry, as are the mass flow rates and heat transfer conditions, it is reasonable to assume that heat transfer coefficients are almost the same on both sides, this makes the collection of data more straightforward. A basic schematic of this type of micro/flow heat exchanger is shown in Figure 1. [2]

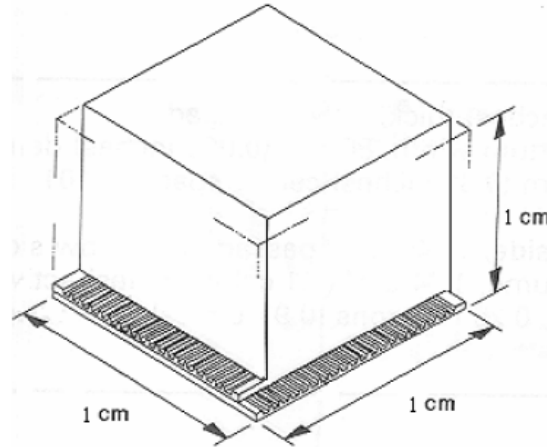


Fig. 1. Schematic of cross flow micro heat exchanger. [3]

Pressure Drop of Fluids. The head produced by typical fans or, in the case of an automobile, the stagnation head associated with an automobile running at 50 mi/hr, both provide a reasonable measure of the typical pressure drop of the air across the heat exchanger. Many fans can produce substantial flow rates across a pressure differential of 175 Pa (0.7 in of water). Therefore, the pressure drop of the air across the heat exchanger was specified at 175 Pa. [1]

The pressure drop of the coolant should be minimized to reduce pumping requirements. Reasonable pressure drops from the literature are 5 kPa, and this is the value specified in this work. The specified value of the pressure drop of the coolant is far less crucial to the design process than that of the air. Typical inlet temperatures for the air and coolant in innovative car radiator designs are 20°C and 95°C, respectively. These values will be used in the following analysis. The cross section of each air channel is a variable. The width of the fins separating adjacent channels is also a variable. For strength and manufacturing considerations, the *minimum* allowed values of both the fin width and the channel width is set at 200 µm. The thickness of the wall separating the coolant and air is not a design variable and is given a value of 125 µm.

The geometry that maximizes heat transfer/frontal area has been calculated for plastic, ceramic, and aluminum micro cross flow heat exchangers. The four design variables for the heat exchanger are the coolant channel width, the air channel width, the fin width, and the fin length. An initial set of these four variables is chosen, and the following procedure is used to calculate the heat transfer. An iterative procedure is used to find the variable set that maximizes heat transfer/frontal area within the set of specified design constraints:

- the hydraulic diameter of the air channel is calculated as $4 A/P$, where A is the cross section of the air channel, and P is the perimeter.
- the relation between pressure drop across the channel and the velocity of air through the channel is given by (1), where the first term on the right-hand side is pressure drop caused by viscous drag, and the second term is related to inlet and exit losses. The constant is the minor loss coefficient k . Both the friction factor f and the bulk velocity V can be iteratively calculated using (1) and given values of Δp , L , ρ , and D_h .

$$\Delta p = \frac{f \rho V^2 L}{2 D_h} + K \frac{\rho V^2}{2} \quad (1)$$

- the Nusselt number is required to determine the convection coefficient on the inner walls of the air channel.

$$Nu = \frac{h_{air} D_h}{k_{air}} = f\left(\frac{L}{D_h Re Pr}, \frac{w}{H}\right) \quad (2)$$

- the flow within the coolant channels is considered fully developed and laminar. The convection coefficient governing the thermal resistance between the coolant and the wall is given by (3), where the hydraulic diameter of the coolant channel D_{h-cool} is a function of and the coolant channel depth. The appropriate length scale for this correlation derived for circular channels is the hydraulic diameter D_{h-cool} .

$$h_{cool} = \frac{4.0 \cdot k_{cool}}{D_{h-cool}} \quad (3)$$

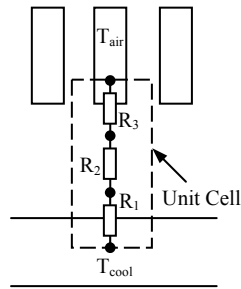


Fig. 2. Thermal resistance network between coolant and air. [1]

- the heat transfer to each air channel can now be calculated. Fig. 2 shows the resistive network between one coolant channel and an air channel. R_1 is the convective resistance at the coolant/wall interface. R_2 is the conductive resistance through the thickness of the wall separating the coolant and air channels. R_3 is the effective convective resistance, based on the inner area of the air channel and the difference in temperature between the base of the fin and the local temperature of the air. The values R_1 , R_2 , and R_3 of and are given by

$$R_1 = \frac{1}{h_{cool}(w+y)L}; R_2 = \frac{a}{h_{wall}(w+y)L}; R_3 = \frac{a}{h_{air}(\eta_f H + w)L} \quad (4)$$

where η_f is the fin efficiency defined by [3]

$$\eta_f = \frac{\tanh\left(\sqrt{\frac{2h_{air}}{yk_{plastic}}} \frac{H}{2}\right)}{\sqrt{\frac{2h_{air}}{yk_{plastic}}} \frac{H}{2}} \quad (5)$$

By symmetry, the total resistance to heat transfer between coolant and a single air channel R_{tot} is one half this sum.

$$R_{tot} = \frac{R_1 + R_2 + R_3}{2} \quad (6)$$

Assuming the coolant temperature does not vary through the thickness of the heat exchanger, the exit temperature of the air is found by manipulating [2]

$$\frac{T_{cool} - T_{air-exit}}{T_{cool} - T_{air-inlet}} = \exp\left(-\frac{1}{\dot{m}_{air} c_{p-air} R_{tot}}\right) \quad (7)$$

where the mass flow rate of the air through the channel is $V \cdot w \cdot H \cdot \rho_{air}$. Finally, the heat transfer to the air through a single channel is given by [1]

$$q_{channel} = \dot{m}_{air} c_{p-air} (T_{air-exit} - T_{air-inlet}) \quad (8)$$

The total heat transfer for the heat exchanger is given by

$$q = N \cdot q_{channel} \quad (9)$$

- the initial assumption that the exit temperature and inlet temperature of the coolant are equal provides an incorrect, slightly high estimate of the total heat transfer. A simple iterative process greatly reduces the error.

a) The number of coolant channels is equal to the height of the heat exchanger F_h divided by distance between channels $F_w \times F_h$. The mean velocity of the coolant V_{cool} through the channels is given by (10) below, where again, correlations for circular tubes are used, and the length scale is the hydraulic diameter of the coolant channel D_{h-cool} :

$$V_{cool} = \frac{D_{h-cool}^2 \Delta P_{cool}}{32 \mu_{cool} F_w} \quad (10)$$

b) With the total number of coolant channels, the cross section of the coolant channels, and the mean velocity through the coolant channels, the mass flow rate of the coolant through the heat exchanger is easily determined. Using (11), the exit temperature of the coolant is calculated.

$$q = \dot{m}_{cool} c_{p-cool} (T_{cool-inlet} - T_{cool-exit}) \quad (11)$$

c) The mean value of the coolant temperature in (11) is the average of $T_{cool-inlet}$ and $T_{cool-exit}$. This mean value of temperature is substituted into (7) as the updated value of T_{cool} . Equations (7)–(10) are repeated, and a new value of is determined $T_{cool-exit}$. The process is repeated iteratively until successive calculations produce values of $T_{cool-exit}$ that differ by less than 0.5 K [1].

3. CONCLUSIONS

Potential applications for the heat exchanger are seen in areas such as microelectronics cooling, aircraft, aerospace cooling and biomedical processes where high heat transfer power are required with little weight and small volume. The use of microchannels in a cross flow micro heat exchanger decreases the thermal diffusion lengths, thereby allowing more heat transfer/volume. A cross flow micro heat exchanger was developed to provide a function similar to a car radiator. The goal of the design was to maximize heat transfer/frontal area for given pressure drops of the air and coolant.

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