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Development of a simplified thermal design calculation computer code of PCHE

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1. Introduction

In order to keep the energy conversion cycle compact, it is necessary to select a heat exchanger type that is compact and has a small pressure drop. Printed circuit heat exchangers(PCHE) have a ability to withstand a high operating temperature and pressure, and high-pressure differentials. They consist of many plates into which the channels are chemically etched. These channels have the shape of a semicircle with diameters of about 1 to 2 mm. There are several kinds of microchannels: continuous model(zigzag model, sinuous curve model), discontinuous model(louvered fin model, modified louvered fin model, S shape fin model).

A computer code PCHESA has been developed based on a heat transfer and pressure drop correlation for the zig-zag model[1]. This study describes the utilized computer model and establishes its validity through a comparison with reported data.

2. Analysis model and results

2.1 Analysis model

A mass conservation equation, one-dimensional energy balance equation, and pressure loss equation are used for the hot and cold sides of channels. The governing equations are of a steady state and the energy balance equation consists of a convection term and a source term for the heat transfer between the hot and cold side flows of channels.

The continuity equation of each control volume for a one-dimensional calculation is as follows:

$$w_h = const.$$

$$w_c = const.$$

where, w_h : hot side flow rate, w_c : cold side flow rate

The flow rate per control volume is assumed to be the total flow rate divided by the total number of channels. This flow rate also applies to the evaluation of a heat transfer. The equivalent hydraulic diameter required for a heat transfer correlation application is determined as

$$D_h = \frac{4A}{p}$$

where, p is the wetted perimeter and is applied to the models.

The energy balance for the *i*-th control volume is expressed by the properties of the *i-1*-th and *i*-th nodes.

Heat transfer rate through a wall is:

$$\Delta Q = U\,\Delta A_c \Delta T$$

Heat transfer rate from the hot side flow is:

$$\Delta Q = w_h\left(h_{h,in} - h_{h,out}\right)$$

Heat transfer rate to the cold side flow is:

$$\Delta Q = w_c\left(h_{c,out} - h_{c,in}\right)$$

where, ΔT : average temperature difference

$$= \frac{\left(T_{h,in} + T_{h,out}\right)}{2} - \frac{\left(T_{c,in} + T_{c,out}\right)}{2}$$

For an overall heat transfer coefficient for each control volume, the lateral heat transfer rate should be the same in all the connected regions of the hot side, wall, cold side of channels as described below.

$$\Delta Q = h_c \Delta A_c \left(T_h - T_1\right) = \Delta A \;\frac{k}{\Delta x}\left(T_1 - T_2\right)$$
$$= h_h \Delta A_h \left(T_2 - T_c\right) = U \Delta A_c \Delta T$$

From the above relations, the overall heat transfer coefficients are obtained as follows;

$$U = \frac{1}{\frac{1}{h_c} + \frac{\Delta x}{k}\frac{\Delta A_c}{\Delta A} + \frac{\Delta A_c}{\Delta A_h}\frac{1}{h_h}}$$

The pressure drop in the mesh is calculated by adding the drop due to a friction by using suitable correlations. Ishizuka et al. [1] have conducted thermal hydraulic tests and proposed empirical correlations for the friction factor and heat transfer coefficient as follows.

- Pressure loss of a Zigzag flow channel

. assumed as a combination of straight pipes and elbows

. Pressure loss of a straight pipe

$$\frac{dP}{dx} = 4f\frac{\rho V^2}{2D}$$

$$f = 0.0014 + 0.125\,\mathrm{Re}^{-0.32}$$

. Pressure loss of a elbow

$$DP_{elbow} = K\zeta\frac{\rho V^2}{2}, \quad \text{K factor : } 1.38 \sim 1.51$$

$$\zeta = 0.946\sin^2(\theta/2) + 2.047\sin^4(\theta/2),$$
bending angle in degree

- Heat transfer coefficient of a Zigzag flow channel

$Nu_{cal} = PF \times Nu$, PF: 2.3 as a heat transfer modification factor of a Zigzag flow

$$Nu = \frac{(f/2)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7\sqrt{\frac{f}{2}}\left(\mathrm{Pr}^{2/3}-1\right)}$$

$$f = \frac{1}{(1.5808\log_e \mathrm{Re} - 3.28)^2}$$

The calculation proceeds in a mesh manner. We evaluated the heat transfer in a mesh of a fixed length by first assuming the fluid temperature and pressure at the end of a mesh and then iterated the assumed and calculated values. The same convergence criterion, 10^{-6}, is applied to the relative variations of the temperature and pressure for each node with respect to the previous iteration values, respectively.

Properties at the *i*-th control volume correspond to the average values of the *i-1*-th and *i*-th nodes

2.2 Results

Table 1 contains the geometry and dimensions of PCHE[1]. The flow channel surface was treated as a smooth surface to calculate the pressure loss.

Table 1. Geometry and dimensions of PCHE[1]

	Hot channel	Cold channel
Plate material	Ss316	Ss316
Plate thickness, mm	1.63	1.63
Number of plates	12	6
Number of channels	144	66
Flow channel bending angle, degree	115	100
Horizontal pitch, mm	4.5	3.62
Pitch of right angle to flow direction, mm	2.97	3.25
Flow channel configuration	Semi-circle	Semi-circle
Wall width, mm	0.6	0.7
Channel width, mm	1.9	1.8
Channel depth, mm	0.9	0.9
Hydraulic diameter of channel, mm	1.15	1.15
Heat transfer area, m^2	0.697	0.356
Cross sectional area of channel, m^2	0.0002	0.000092
Channel active length, mm	1000	1100
Inlet and outlet part length, mm	49	46.5
Channel length, mm	896	896

The details of the comparison of the test data and the calculation values are presented in Table 2. Co_2 flow rates both in the cold and hot side flow channels of the PCHE are the same. It showed that the calculated when compared with the test data was 0.99 – 1.0 for the temperature, 0.97 – 1.2 for the pressure loss and 0.99 – 1.0 for the heat load. The overall heat transfer coefficient was 387, 950 W/(m^2K) for case1 and case2 respectively. The heat exchanger effectiveness was 0.98, 0.99 respectively.

Table 2. Comparison of the test data and calculation values

		Case1		Case2	
		test	calculated	test	calculated
Flow rate	Kg/h	33.5		87.0	
P_{hi}	MPa	2.49		3.23	
P_{ci}	MPa	7.44		10.09	
T_{hi}	℃	279.8		280.1	
T_{ho}	℃	111.5	111.47	109.9	110.3
T_{ci}	℃	107.9		108.2	
T_{co}	℃	262.3	259.3	252.8	252.7
DP_c	kPa	20.09	19.44	80.35	86.88
DP_h	kPa	5.99	6.58	25.91	30.99
Q	kW	1.624	1.624	4.324	4.312

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