High Performance Heat Exchanger For Thermoelectric Cooling With Large Heat Loads

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Abstract

This paper discusses the design and development strategies of a novel micro-heat exchanger technology suitable for thermoelectric refrigeration applications with large heat loads. Incorporating narrow (micro-scale) fluid streams for heat exchange, the presented concept harnesses excellent heat transfer characteristics of microchannel flow to enhance thermal performance. Simulation models are developed for the micro-heat exchanger to assess the influence of critical system variables on heat transfer rates and pumping power, and to ascertain optimal parametric combinations for thermoelectric applications. Predicted thermal behaviour is experimentally verified and validated. Test results conclusively show unprecedented thermal performance levels with this micro-heat exchanger technology setting a new industry benchmark for thermoelectric cooling applications.

Introduction

In line with the development of "CFC-free" alternatives for refrigeration, thermoelectric cooling (Peltier Effect) is widely regarded as the only pragmatic solution that could eventually replace conventional vapour-compression systems realising sustainable environmental benefits. However to-date, the technical and commercial viability of thermoelectric cooling is by and large constrained by grossly ineffective heat dissipation mechanisms that interface Peltier modules to coolants in existing heat exchanger technology. Such designs essentially incorporate rudimentary natural/forced convective methods induced by cooling fans that deliver dismally unattractive low heat flux levels. Poor thermal performance of conventional heat exchange techniques is characteristically manifested as excessively high thermal resistance in the heat flow path from Peltier to coolant in thermoelectric devices. Even the best of commercial thermoelectric cooling units exhibit a thermal resistance of 0.14 to 1.5 K/W [1,2,3,4,5,6].

Impeded heat dissipation arising from high thermal resistance causes Peltier modules to operate at elevated temperatures making them overheat and eventually fail with increased heat loads. Critically underpinned by the limitations of heat exchanger technology, commercial manufacturers have expediently avoided high-capacity thermoelectric cooling ventures and have resorted to development of devices with small heat loads such as, computer CPU coolers, medicine cold storage units and aquarium cooling systems [1,2,3,4,5,6].

In developing effective heat exchangers for commercial high-capacity thermoelectric cooling, proposed designs will have to have: (a) a Peltier-to-coolant thermal resistance threshold not exceeding 0.1 K/W; (b) low fluid pump power achieve appropriate overall Coefficient of Performance (COP), and (c) ability to scale-up in terms of heat handling capacity to accommodate commercial heat load levels. Appropriate combination of these factors will determine the desirable degree of heat pump performance and underline the economic viability of heat high-capacity thermoelectric cooling [7].

In recent years, only one breakthrough-design of a heat exchanger has been reported in literature addressing the abovementioned performance target issues. From an original design by Hydrocool, Matsushita Refrigeration Company of Japan has developed a radically new compact heat exchanger incorporating a rotary fluid pump and a special manifold. In this design, the coolant is spun at high speed with a vaned-rotor and forced to flow radially over the heat transfer surface of the heat exchanger. Test results indicate a much reduced thermal resistance of about 0.03 K/W [8] making this pump manifold design stands well above the other designs in terms of thermal performance. However, it exhibits several crippling limitations for high-capacity refrigeration systems. When multiple units are deployed to handle large cooling loads, the Matsushita concept demands very large pump powers and fluid flow rates significantly lowering the overall COP. Also inherently, the design requires specific dimensions for optimum thermal performance preventing extension of this concept for scaled-up versions. These technological constraints have limited Matsushita commercial product development to small-scale 60-litre thermoelectric bar fridges for hotel rooms.

The patented Hydrocool micro-heat exchanger concept presented in this paper overcomes all identified performance barriers of previous thermoelectric heat exchanger designs and lowers the Peltier-to-coolant thermal resistance threshold to a new industry benchmark, as outlined below.

Hydrocool micro-heat exchanger concept

The Hydrocool micro-heat exchanger technology is broadly based on the proven heat removal techniques for cooling miniature electronic components using microchannel fluid flows. Studies indicate that the flow through micro/miniature passages can deliver 60 times higher heat transfer rates than those in larger channels [9,10,11,12]. Achievable heat flux levels of such flows are in excess of 100 W/cm^2 and easily surpass the heat load requirements of heavy-duty thermoelectric cooling. However, high fluid pressure drop (>200 kPa) inherently associated with microchannels is a major drawback that renders poor COP for thermoelectric cooling applications, where both heat exchanger performance and heat pumping efficiency are high-priority considerations.

Therefore, microchannel heat transfer methods cannot be directly employed for thermoelectric cooling except with appropriate modifications.

The Hydrocool micro-heat exchanger concept is the first in the industry to capture microchannel heat transfer enhancement as a development strategy for high-performance heat exchangers for thermoelectric cooling systems with large cooling loads. The design methodology trades off some degree of microchannel heat transfer enhancement to gain lower fluid pressure drop. In achieving this, it incorporates slightly larger fluid flow channels (0.1-1.0mm) than conventional sizes of microchannels (0.01-0.5mm). Proper selection of channel dimensions warrant sufficiently strong microchannel behaviour to be available in fluid passages while reducing pump power to accommodate high COP needs of thermoelectric cooling applications. Tapping into the vast knowledge base of microchannel heat transfer, this design strategy opens up a whole new development direction for high performance thermoelectric micro-heat exchangers.

Conceptually, the Hydrocool micro-heat exchanger consists of a multitude of narrow rectangular fluid passages embedded in an insulated solid metal block, as shown in Fig. 1. Externally applied heat is conducted through the channel walls and is convected to the coolant within channels. Propagating heat in the geometry overcomes the conductive thermal resistance in channel walls and the convective resistance at the solid-fluid interface. The overall thermal performance of the micro-heat exchanger is determined by the total thermal resistance along the heat flow path wherein low values yield unimpeded heat delivery.

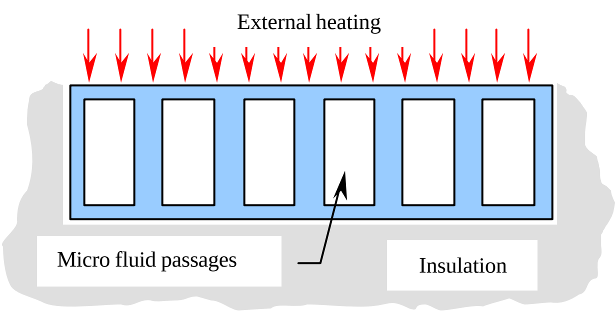

Fig. 1 Concept diagram of Hydrocool micro-heat exchanger

Since convection is generally a weaker mode of heat transport than conduction, the convective heat transfer within the coolant flow predominates the overall thermal resistance, and any enhancement therein will effectively improve thermal performance of the heat exchanger. While microchannel fluid flow characteristics intensify convective heat transfer process in coolant flow, a highly conductive solid block is desirable in reducing thermal resistance in channel walls.

Simulation models

As outlined, the heat transfer process in the proposed micro-heat exchanger is a complex interactive behaviour involving heat conduction and convection. Adding to this complexity is the axial heat conduction in the direction of coolant flow through the heat exchanger. Therefore, prospects for complete analytical model development are remote, and two extremes of modelling methodologies are attempted. In the most accurate, yet time-consuming approach, numerical simulations were carried out with the high-end Computational Fluid Dynamics (CFD) software FLUENT using appropriate solver models. In the simplified and less-accurate approach, axial heat conduction was neglected to develop a one-dimensional (1-D) model of heat flow. The advantage of the latter model is that it can be executed as a simple computer programme or a Microsoft Excel macro spreadsheet permitting quick turnaround time for a range of case studies.

(a) Computational Fluid Dynamics simulation

In the CFD approach, the heat conduction through the solid block (including axial heat conduction) and the convective fluid flow through micro-scale passages were solved as a conjugate heat transfer problem wherein solid and fluid continua were simultaneously considered with Finite Volume (FV) technique. Depending upon the coolant flow regimes, appropriate laminar or turbulent solver models were used. These up-to-date models have shown to be accurate and valid down to 50 μm of microchannel diameter [13]. Due to ill-proportioned nature of channel dimensions, adaptive grid spacing was employed in which areas of steep flow gradients were better represented by finer and non-standard cells shapes.

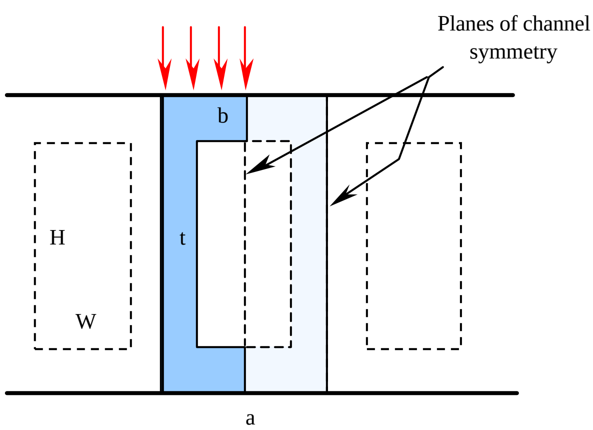

Fig. 2 One-dimensional simulation model

(b) One-dimensional simulation

This model is essentially based on the assumption that, any axial heat conduction along channel length is negligible, which is in fact the case with a highly conductive solid block. Identifying planes of symmetry and representative one half of a channel (shaded), as depicted in Fig. 2, the analysis considers two one-dimensional heat flow paths.

The heat flow through the sidewall thickness is the first of the two paths that basically behaves like a fin with an insulated tip delivering heat to the coolant along the inner channel surface. The second path is the direct heat flow to the coolant through the base thickness where the external heating is applied. These two "finned" and "un-finned" components culminate to form the total heat flow and the overall thermal resistance of the geometry.

Using standard fin equations [14], the overall thermal resistance of the micro-heat exchanger geometry R, can be written as,

$$R = \frac{4}{hL\left[\eta H + (1+\eta)W\right]} + \frac{4b}{kLa} \qquad (1)$$

where, $\eta = \frac{\tanh(mx)}{mx}$ with $m^2 = \frac{h}{kt}$ and $x = \frac{(2H+W)}{2}$, and L is the channel length, h is the convective heat transfer coefficient in the channel and k is the thermal conductivity of the solid block. Other length dimensions are given in Fig. 2.

In evaluating the convective heat transfer coefficient within the coolant flow, three established heat transfer correlations were used. They are:

(i) $Nu = 3.66 + \frac{0.0668\,(D/L)\,Re\,Pr}{1 + 0.04[(D/L)\,Re\,Pr]^{2/3}}$, that considers flow developing conditions [15] and applicable for circular ducts;

(ii) $Nu = 1.86\left[\frac{Re\,Pr}{L/D}\right]^{1/3}\left[\frac{\mu}{\mu_s}\right]^{0.14}$ that is similar to (i) with a better range of applicability [16], and

(iii) $Nu = g_o + g_1\beta + g_2\beta^2 + g_3\beta^3 + g_4\beta^4 + g_5\beta^5$ with g_o =8.235, g_1 = -16.819, g_2 = 25.327, g_3 = -20.079, g_4 = 8.3064, and g_5 = -1.3622, where β is the channel aspect ratio (H/W). This correlation [17] provides heat transfer coefficient under fully developed flow conditions in rectangular channels over the aspect ratio range from 1 to ∞ and does not consider developing length of flow passages.

In optimising the thermal performance of the micro-heat exchanger, the overall thermal resistance was computed using both simulation methods by varying channel height, width and wall thickness, and coolant flow rate. The effect of the solid block thermal conductivity was also examined by considering both copper and aluminium. Water was used as the coolant.

Experimental apparatus

The experimental set up comprised of a micro heat exchanger, which is externally heated by a heater plate, and a fluid flow circuit with a micro-pump and a controller, which maintained the coolant flow at a prescribed rate. A turbine flow meter measured the flow rate in the circuit. Electrical resistors embedded in the heater plate provided heating, which was calculated from electrical energy input. Average heater interface temperature was obtained by a thermocouple array in the heater. Fully mixed inlet and outlet coolant temperatures were recorded with thermocouples in fluid manifolds. A micro-manometer was attached to obtain pressure drop across the test module. Thermal contact between the heater plate and the micro-heat exchanger was improved by applying thermal paste. The entire heat exchanger-heater assembly was heavily insulated and kept in a temperature-controlled chamber during tests. Data-logger with LabView software was employed to acquire and store coolant flow rate, external heat input, measured temperatures and pressure drop in the test set up.

Results & Discussion

With water as the working fluid, the micro-heat exchanger performance was simulated and tested within a flow range of 0.5 to 4 l/min. The inlet water temperature was generally set to be 3 °C or 27 °C. An external heating power of 15-20 W was applied over the heat exchanger area of 40x40 mm.

Figs. 3 and 4 show comparison of typical values of thermal resistances obtained by the CFD and 1-D simulation models. Excellent agreement is noted between the two methods except when the channel aspect ratio H/W becomes high. This is largely attributed to the use of heat transfer correlations that are generally applicable for circular duct to slender rectangular passages in the 1-D model. CFD analysis confirms that, owing to short flow fluid length and high solid thermal conductivity, the effects of axial heat conduction are negligibly small adding more credibility to the 1-D analysis.

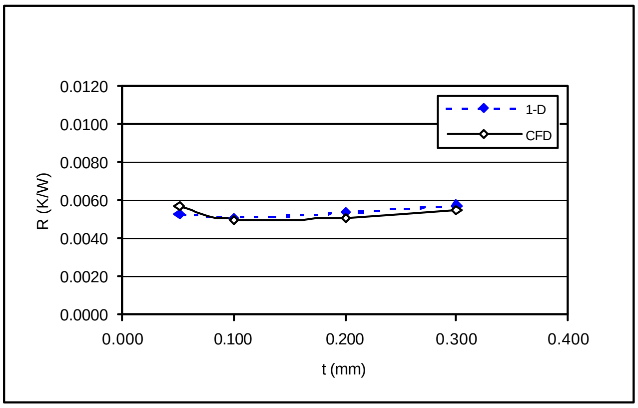

Fig. 3 Variation of thermal resistance with wall thickness H=2.0 mm, W=0.1 mm, flow rate 2 l/min

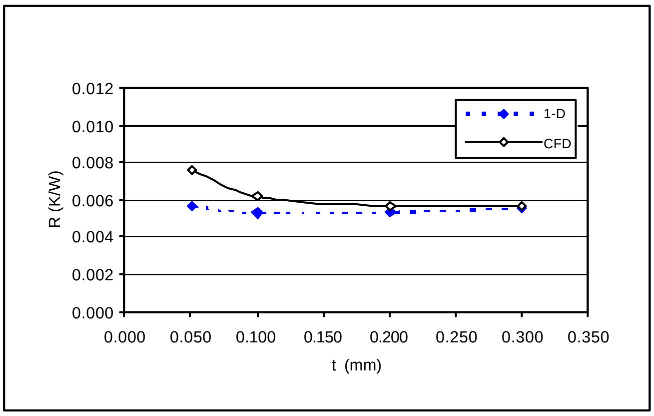

Fig. 4 Variation of thermal resistance with wall thickness H=4.0 mm, W=0.1 mm, flow rate 2 l/min

Variation of thermal resistance with channel height is illustrated in Fig. 5. It is evident that, as the channel height is increased, thermal resistance initially falls and subsequently remains unchanged. This suggests that the "fin behaviour" of channels will have a saturation effect indicating a practical limit for channel heights and achievable thermal performance of the heat exchanger. Similar characteristics are observed with all other channel widths and flow rates examined.

As shown in Fig. 6, reduced channel width causes rapid increase in micro-heat exchanger pressure drop. This again imposes a limit on useable channel sizes for a specific heat exchanger application requiring through evaluation of thermal benefits against adverse fluid pump powers.

Typical experimental values of thermal resistances are given in Table 1. For all test cases, they remain within 0.01-0.02 K/W and are the lowest-ever reported for a thermoelectric-type heat exchanger. Simulation were characteristically seen to under-predict measurements by about 0.004 to 008 K/W, which is chiefly attributed to the variability of heater interface contact resistance. Therefore, the measured thermal resistances are very conservative in magnitude and verify that the microchannel heat transfer is a practical and effective enhancing mechanism for thermoelectric cooling systems.

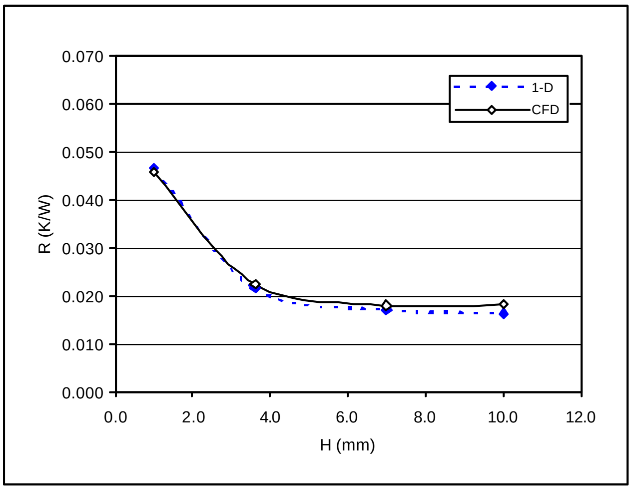

Fig. 5 Variation of thermal resistance with channel height
W=0.4 mm, t=0.85 mm, flow rate 0.5 l/min

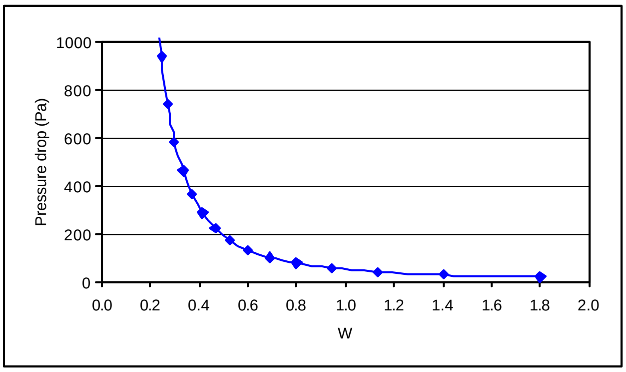

Fig. 6 Variation of fluid pressure drop with channel width
H=4.0 mm, t=0.2 mm, flow rate 0.5 l/min

Table 1: Comparison of experimental data with predicted results at 2.0 l/min

W (mm)	t (mm)	H (mm)	R_{Expt} (K/W)	R_{prd} (K/W)
0.40	0.80	3	0.0220	0.0175
0.34	0.20	7	0.0240	0.0176
0.18	0.40	7	0.0120	0.0081
0.18	0.40	4	0.0120	0.0090
0.10	0.30	3	0.0095	0.0055
0.10	0.13	7.3	0.0140	0.0106

Conclusions

The Hydrocool micro-heat exchanger concept clearly illustrates a practical and effective way to adopt microchannel heat transfer characteristics in developing a high-performance heat exchanger for thermoelectric cooling. With appropriate selection of operating parameters, this micro-heat exchanger design offers thermal resistances of the order 0.01-0.02 K/W and low fluid pump powers. Modular and compact nature of the concept provides the flexibility to scale-up to meet high heat loads of heavy-duty thermoelectric cooling without adverse performance deterioration. These attributes set the Hydrocool micro-heat exchanger concept well above previous heat exchanger technologies for thermoelectric cooling systems. Hydrocool's prototype of a 126-litre thermoelectric refrigerator with a freezer that can reach -25 ^{o}C is a strong testament to the application potential of this novel micro-heat exchanger technology.

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