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Study of transient forced convection heat transfer from discrete heat sources in a FC-72 cooled vertical channel

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Abstract

Experiments are performed to study the transient forced convection heat transfer from a four-in-line chip module that are flush-mounted to on one wall of a vertical rectangular channel using FC-72 as coolant. The flow covers the wide range of laminar flow regime with Reynolds number based on heat source length, from 800 to 2625. The heat flux ranges from 1 to 7 W·cm^{-2}. The heat transfer characteristics are studied and correlations are presented. The transient correlation for overall data recommended is $Nu_\ell = 0.776(Pe_\ell^{1/3})Fo^{-0.74}$. Finally the data obtained from FC-72 are compared with the data from water coolant and found that the Nusselt number data from FC-72 are higher than those from water.

Keywords: Forced convection; Discrete heat sources; Electronics cooling; Steady-state heat transfer; Transient heat transfer

1. Introduction

The problem of transient forced convection from discrete heat sources in vertical channel has received considerable attention from researchers in many diverse fields of applications. With the rapid technological development, the circuit integration density and the rate of heat dissipation by an electronic component have increased. In the coming years these heat flux may exceed 100 W·cm^{-2} [1]. With increasing power density within the chips, as well as the attendant tendency to design chips closely in planar arrays, more stringent requirements in thermal management are needed. This has prompted the consideration of liquid cooling, instead of the prevalent air-cooling, to remove the increasing cooling load from high-power electronic chips [2–4].

The relative performance and features of cooling modes for different liquids are described by Bar-Cohen [5]. It is found that Fluorocarbon liquids (e.g., FC-72, FC-86, FC-77, etc.) are generally considered to be the most suitable liquids for direct immersion cooling. These coolants are clear, colourless per-fluorinated liquids with a relatively high density and low viscosity. They also exhibit a high dielectric strength and a high volume resistivity. The boiling points for the commercially available “Fluorinert” liquids manufactured by 3M Company [6] range from 30 to 253 °C.

The relative magnitude of the heat transfer coefficient is also affected by the mode of convection. The forced convection has proven to be reliable to remove heat from high-power chips. The transient characteristics are of importance in the thermal systems during the power-on and power-off periods. At these events, fluid flow and heat flux change with time, leading to temperature changes. As electronic components, and hence the system performance and integrity, are sensitive to temperature, there is therefore a need to investigate the transient thermal behaviour of the system, in order to determine the extent of deviation from the normal conditions, especially during power-on period.

Fluid flow over discrete heat sources has different characteristics from the heated whole wall. The average Nusselt

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Nomenclature

Symbol	Description	Unit
A	area of the channel cross section, WH	m^2
Bi	Biot number, defined by Eq. (9)	
C	coefficient in correlations	
c_p	specific heat of liquid at constant pressure, defined by Eq. (3)	
Fo	Fourier number, defined by Eq. (8)	
g	gravitational acceleration	$\mathrm{m \cdot s^{-2}}$
H	height of the channel	m
H_c	height of the chip	m
h	heat transfer coefficient	$\mathrm{W \cdot m^{-2} \cdot K^{-1}}$
k	thermal conductivity of liquid, defined by Eq. (1)	$\mathrm{W \cdot m^{-1} \cdot K^{-1}}$
k_c	thermal conductivity of chip (copper)	$\mathrm{W \cdot m^{-1} \cdot K^{-1}}$
ℓ	length of heat source	m
m	exponent of Fo	
Nu_ℓ	Nusselt number based on heat source length, defined by Eq. (5)	
n	exponent of Pe_ℓ	
Pe_ℓ	Peclet number based on heat source length, defined by Eq. (7)	
Pr	Prandtl number, $= \nu/\alpha$	
Q	volumetric flow rate	$\mathrm{m^3 \cdot s^{-1}}$
q''	heat flux	$\mathrm{W \cdot m^{-2}}$
Re_ℓ	Reynolds number based on heat source length, defined by Eq. (6)	
SD	standard deviation	
t	time elapsed after the power-on	s
T_{in}	channel inlet temperature	K
T_{wall}	chip wall temperature	K
U	velocity of flow, $= Q/(WH)$	$\mathrm{m \cdot s^{-1}}$
W	width of the channel	m

Greek symbols

Symbol	Description	Unit
α	thermal diffusitivity, $k/\rho c_p)$	$\mathrm{m^2 \cdot s^{-1}}$
ρ	density of fluid, defined by Eq. (2)	$\mathrm{kg \cdot m^{-3}}$
μ	dynamic viscosity, defined by Eq. (4)	$\mathrm{kg \cdot (ms)^{-1}}$
ν	kinematic viscosity, $= \mu/\rho$	
β	coefficient of thermal expansion	$\mathrm{K^{-1}}$

Subscripts

Symbol	Description
in	inlet
wall	heater wall

number for discrete heating is substantially higher than that of uniform heating [7]. For the case of discrete heating the Nusselt number fluctuates drastically reaches a very high value in the unheated regions during the early transient and becomes smooth with increasing time [8]. The analyses of heat transfer in vertical channel with discrete heat sources are of help in better understanding of the transient thermal behavior of electronic chips and the correlation equations are useful to the designers of such components.

Samant and Simon [9] investigation experimentally the heat transfer from a small heated patch to a sub-cooled fully-developed turbulent flow of R-113 and FC-72. Garimella and Schlitz [10] analysed experimentally the enhancement of forced convection heat transfer in a rectangular duct from discrete heat sources with water and FC-77. The two-dimensional transient natural convection heat transfer in a square cavity, where the opposing sidewalls were subjected to an arbitrary time variations in temperature was investigated by Hyun and Lee [11]. Shim and Hyun [12] analysed numerically the time-dependent adjustment of natural convection in a square cavity with internal heat generation. Abu-Hijleh et al. [13] investigated numerically the transient conjugate forced convection in channel flow and observed that the dimensionless parameters Peclet number and Biot number have significant on the dimensionless Fourier number. Zueco et al. [14] studied numerically the transient forced convection in pipe exposed to a step change in the temperature. Sucec [15] investigated numerically the transient forced convection in parallel plate duct when there was sinusoidal generation with axial position in the duct wall and observed that the transient Nusselt number depended on time. The literature survey reveals that no results have been reported for transient forced convection involving discrete heat sources using FC-72 coolant.

The authors reported thermal behavior of electronic chips during power-off [16], pump-off [17], transient natural convection [18] and power-on [19] transient heat transfer using water as coolant. Since this basic arrangement has not been studied in the transient forced convection heat transfer using FC-72 coolant, this provides motivation towards the present study. The objective here is to analyze experimentally the power-on transient forced convection heat transfer from a linear array of flush-mounted discrete heat sources in a vertical up-flow rectangular channel for liquid coolant of FC-72. The effect of heat flux and geometric parameters such as chip number are investigated in the transient regimes. Empirical correlations are reported for individual chip as well as for overall data. Finally a fair comparison is performed with the results of water cooling.

2. Handling of experimental data

In the analyses, the thermophysical properties of FC-72 are allowed to vary with temperature. The functional relations between thermal conductivity k, density ρ, specific heat c_p, and dynamic viscosity μ with temperature are [6]

$$k = 0.001 \times (90 - 0.11 T_{\text{wall}}) \tag{1}$$

$$\rho = \frac{340}{0.1619 + 3.406 \times 10^{-5} T_{\text{wall}} + 3.406 \times 10^{-7} T_{\text{wall}}^2} \tag{2}$$

$$c_p = 561.3 + 1.704 T_{\text{wall}} - 2.381 \times 10^{-4} T_{\text{wall}}^2 \tag{3}$$

$$\mu = 2.702 \times 10^{-2} - 2.1734 \times 10^{-4} T_{\text{wall}} + 5.9832 \times 10^{-7} T_{\text{wall}}^2 - 5.5694 \times 10^{-10} T_{\text{wall}}^3 \tag{4}$$

Nusselt number based on heat source length is defined as

$$Nu_\ell = \frac{h\ell}{k} = \frac{q''\ell}{k(T_{\text{wall}} - T_{\text{in}})} \tag{5}$$

Reynolds numbers based on heat source length is defined as

$$Re_\ell = \frac{U\ell}{\nu} \tag{6}$$

Peclet number based on heat source length is defined as

$$Pe_\ell = Re_\ell \times Pr \tag{7}$$

Fourier number is defined as

$$Fo = \frac{\alpha t}{H_c^2} \tag{8}$$

Biot number is defined as

$$Bi = \frac{hH_c}{k_c} \tag{9}$$

3. Experimental apparatus and procedure

The experimental facilities consist of a test section apparatus and instrumentation similar to those employed by [16–20], for convenience reproduced in Fig. 1(a) and (b). Experiments are conducted in a closed-loop liquid cooling flow facility with a vertical up-flow channel as shown in Fig. 1(a). The temperature at the test section inlet is maintained constant by means of the heat exchanger and the immersion heater in the reservoir and is measured just prior to the test section by a K-type thermocouple. Fig. 1(b) shows the cross sectional view of the majority of the 120 mm test section that is constructed from Plexiglas with 20 mm width (W) and 5 mm height (H). The multichip module is machined from high temperature Teflon (low thermal conductivity of 0.4 W·m^{-1}·K^{-1}). The Chip 1 refers to the upstream heater of the channel is located 700 mm downstream of the channel inlet, providing a minimum hydrodynamic entry length of 50 hydraulic diameters. This allows the fluid laminar boundary layer to be fully-developed before the first chip. The surfaces of the chips are mounted in the Teflon substrate module and the chips are positioned in the centre of the channel wall with spacing of 5 mm between the edges of the chip and the channel sidewalls. Each chip is fabricated from Oxygen-free Copper with the height, $H_c = 9$ mm and length, $\ell = 10$ mm. The dimensions of the chip surface in contact with the liquid are 10 mm × 10 mm. A film resistive heater is attached to each chip and is controlled by a voltage transformer connected in series. As such four similar voltage transformers are used for the four chips. Variations in the heater powers between the different heaters are negligible. The resistors are attached to the underside of the chips with thermally conducting epoxy. Teflon is also used to isolate the module from the surroundings to minimize heat loss. A Teflon block is also threaded to accommodate four screws to ensure that the resistors are attached well enough to the chips.

Prior to performing the experiments, the chip surfaces are polished with a water proof abrasive silicon carbide paper that has particles of average size 10 µm and should create a uniform surface texture on each chip. Two chromel-alumel thermocouples of the K-type are embedded along the chip centerline in the flow direction at a depth of 0.5 mm under the chip surface and are located 2 mm apart from upstream and downstream edges of the chip respectively. The mean wall or surface temperature of each chip is the average of the temperatures measured by the two thermocouples. These data are measured, recorded and reduced by an automatic PC based data acquisition system. All the walls of the channel are adiabatic, except the embedded chips that are heated with constant heat flux. It is worth mentioning here that the surfaces outside the heat source are adiabatic.

The configuration of simulated chips tested in this study is always flush-mounted and all the four chips are heated simultaneously at constant heat flux. The procedure for obtaining data in the single-phase experiments is to start with the flow rate ranging from 8×10^{-3} to 20×10^{-3} m^3·h^{-1} with an inlet temperature $T_{\text{in}} \approx 22\,^\circ\text{C}$. The temperatures of the simulated chip are allowed to reach steady-state, the electrical power to the chips are then switched on, the chip temperature will increase sharply and will reach steady-state with increase of time. In the experiments, the Biot number Bi always varies from 0.003 to 0.007 that prevails the isothermal conditions on the chips [16–19].

4. Estimated uncertainties

In general, heat losses for liquid cooling of simulated chips have been found to be negligible, such as in the studies of [21–23]. In the present analyses, the heat losses are determined by measuring the surface temperature of Teflon exposed to the surroundings and the temperature of ambient air, and are based on the assumption that the heat losses by conduction in the multichip module are equal to the heat dissipation by natural convection from the surface of the multichip module to the surroundings. An estimation of the overall uncertainty in the experimental data is made using standard techniques for single-sample measurements of [24], and the propagations of the uncertainties into dimensionless parameters are then determined. The study reveals that the uncertainties in q'', Re_ℓ, Nu_ℓ, Pe_ℓ, Fo to be less than 5.0%, 3.8%, 6.8%, 3.8% and 4.0%, respectively. These values are based on the assumption of negligible uncertainty in the relevant fluid properties.

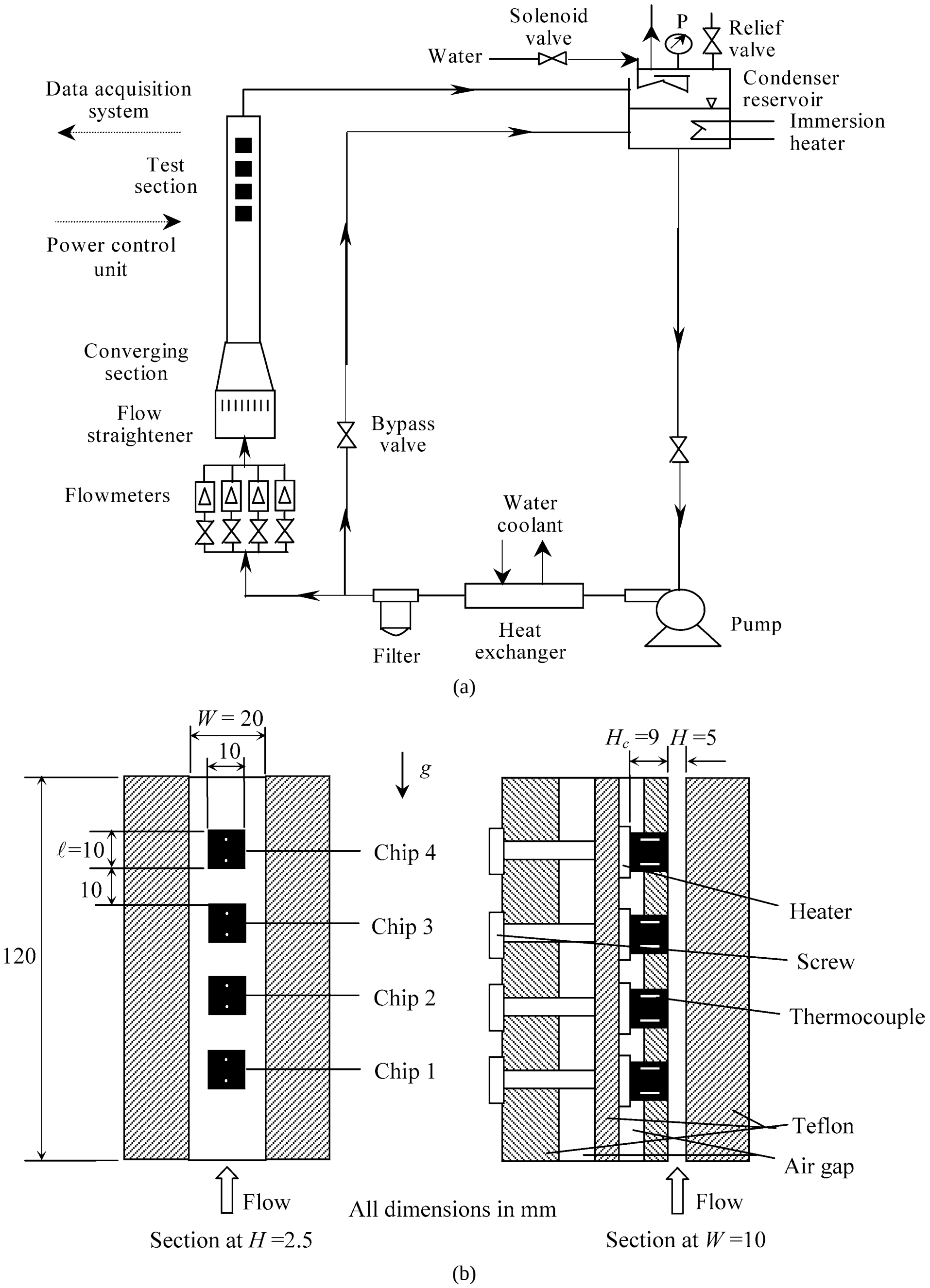

Fig. 1. Schematic of test facility and heaters details: (a) schematic of the test facility; (b) simulated chips mounted on one side of module.

5. Experimental results and analyses

To ensure the test rig condition, the steady-state forced convection results for water cooling are compared with the open literature. For water cooling the steady-state forced convection results are compared with Tso et al. [20] and Shah and London [25]. It is found a fare agreement of 5% discrepancy with the present results for steady-state forced convection [20], the results are reproduced in Fig. 2. However, it is ensured that the test rig is in good working condition. The analyses are then followed by transient operations. Fig. 3 shows the temperature history of the four chips for power-on transient operations.

For analyses the transient heat transfer regime for 75 s are taken after the power-on, while keeping the pump power-on. The transient time 75 s are selected based on the nature of Nu_ℓ variations in Fig. 4. It is seen that after 75 s the Nu_ℓ of the four chips do not change significantly with time. The variations of Nusselt number Nu_ℓ as a function of time in the transient regime for four chips are plotted in Fig. 4, for the experimental condition of $Re_\ell = 1575$ and $q'' = 5\ \mathrm{W{\cdot}cm^{-2}}$. It can be seen that the Nu_ℓ decreases continuously with time during the entire power-on transient operation. Analysing

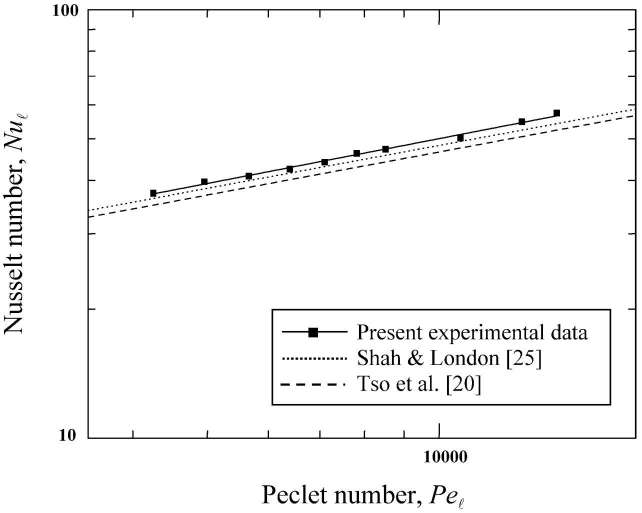

Fig. 2. Steady-state forced convection results for water cooling.

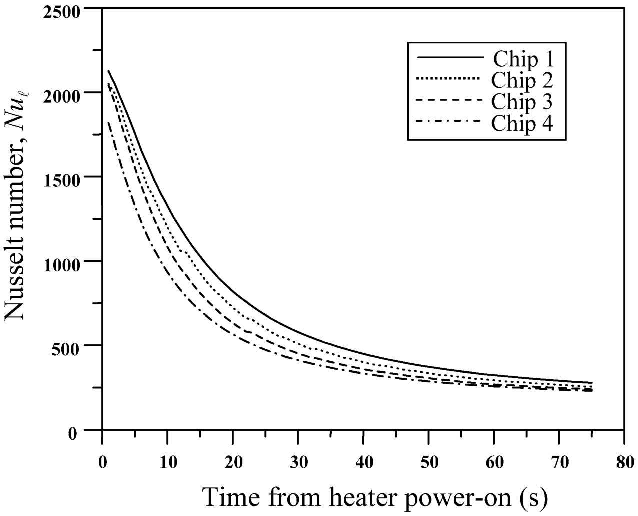

Fig. 4. Nu_ℓ variations with time in the transient regime.

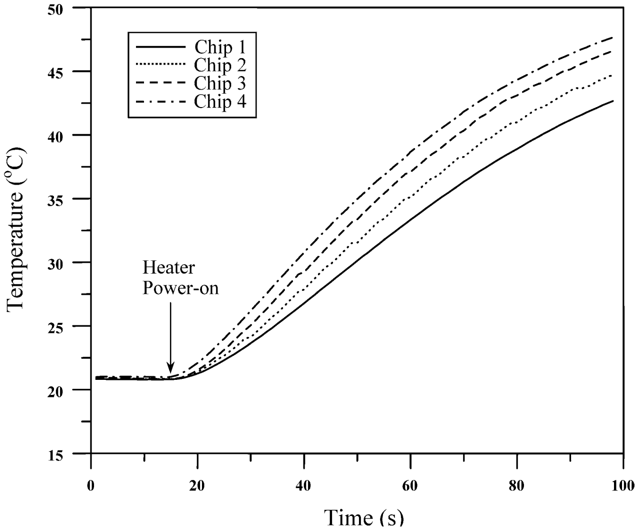

Fig. 3. Transient temperature history.

this situation, it is observed that, a significant drop of Nu_ℓ is observed at the beginning of the power-on up to 25 s. This may be due to the sharp increase of chip wall temperature with time. The transient conduction into the liquid may also contribute for this variation. It is also observed that after 25 s the chip temperatures come toward the quasi-equilibrium and do not change significantly with time. These observations are consistence with the observations of [14]. The same phenomenon occurs for the test case of q'' from 1 to 7 W·cm^{-2} and Reynolds number Re_ℓ from 800 to 2625. It is also found that at the beginning of the power-on, the Nu_ℓ of the second, third and fourth chips are about 96%, 89% and 86% of the first chip respectively, and at the end of experiments (at 75th's) they are about 92%, 86% and 83% of the first chip respectively. This conveys the fact that as the chip number increases, the difference between the neighbouring chips become smaller and have reached a chip number independent, since there is a little difference of 3% in values between third and fourth chip at 1st s and 70th s. This observation is similar to the other transient heat transfer studies [16–19].

The experimental data obtained for all the test cases are used for the development of empirical correlations. For transient forced convection in horizontal channel, the Peclet number has significant effects of heat transfer [13,14]. It is also stated that the transient Nusselt number depends on time [15]. However, in the present analyses, the combined effect Peclet number Pe_ℓ and time dependent Fourier number Fo on Nusselt number Nu_ℓ in the transient regime is considered. Thus the correlation equation can be proposed as the following form [19]

$$Nu_\ell = C Pe_\ell^n Fo^m \tag{10}$$

The exponent n of the Peclet number of Eq. (10) is taken to be $1/3$, which has been generally accepted for steady-state forced convection laminar flow [20,25] and power-off [16] and power-on [19] transient heat transfer studies. Having selected n as $1/3$, simplifies the Eq. (10) as the following form

$$Nu_\ell = C Pe_\ell^{1/3} Fo^m \tag{11}$$

The coefficient C, and exponent m, of the correlation Eq. (11) for the four chips are determined by using the linear fit method and checking the independence of C and m on the q'' and Re_ℓ to correlate the transient heat transfer data in the transient regime. To observe the linear fit lines, the R-squared value for four chips are determined and tabulated on Table 1. It is found that the R-squared values are near to 1 that ensures the good linear fit. The Fo versus $[Nu_\ell/Pe_\ell^{1/3}]$ in the transient regime is shown in Fig. 5 for the conditions of $Re_\ell = 1575$ and $q'' = 5$ W·cm^{-2}, where curve lines are the experimental results and the straight lines are linear fits.

The above procedures are followed to determine the values of C and m in Eq. (11) for each experimental condition and for each chip. The average of these results are taken as the value for each chip. Finally, the relations between C and

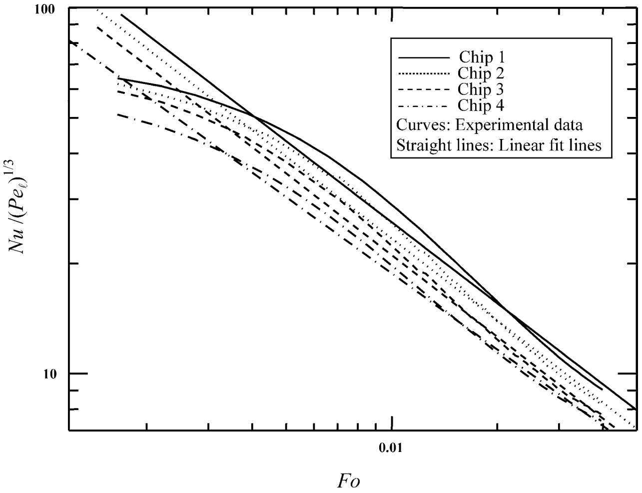

Fig. 5. Linear fit results for four chips.

Table 1
R-squared values for four chips

	Chip 1	Chip 2	Chip 3	Chip 4
R-squared value	0.978	0.984	0.990	0.992

Table 2
Mean values of *C* and *m* for four chips

	Mean, *C*	*SD* of *C*	Mean, *m*	*SD* of *m*
Chip 1	0.877	0.025	−0.735	0.023
Chip 2	0.776	0.033	−0.741	0.034
Chip 3	0.759	0.021	−0.746	0.026
Chip 4	0.694	0.027	−0.752	0.038
Overall recommended	0.776	0.030	−0.744	0.035

m with respect to q'' and Re_ℓ for four chips are also determined by the linear fit method. It is found that in all cases the slopes are always less than 0.02. Thus, it can be concluded that the C and m are independent on Re_ℓ and q''. The mean values of C and m for the four chips as well as for overall data are given in Table 2. The overall recommended correlation for the present conditions is given in Eq. (12) where the average standard deviation of C and m are less than 5%.

$$Nu_\ell = 0.776\left(Pe_\ell^{1/3}\right)Fo^{-0.74} \tag{12}$$

6. Comparison with water cooling studies

Fig. 6 shows the Nusselt number Nu_ℓ variations with time for water and FC-72 in the power-on transient regime for the experimental condition of $Re_\ell = 1575$ and $q'' = 5\ \text{W}\cdot\text{cm}^{-2}$. It is seen that the data from FC-72 are similar to the data from water for four chips, and the data from FC-72 are higher than those from water. It can be seen that at the beginning of power-on the Nu_ℓ data of FC-72 of the first, second, third and fourth chips are about 34%, 43%, 50%, 55% and at the end of experiments (at 75th s), 74%, 75%, 76% and 78% higher than those for water data, respectively. However, an overall increase of 70% in values is obtained by using FC-72. These observations are consistent with the observations of Samant and Simon [9] and Garimella and Schlitz [10].

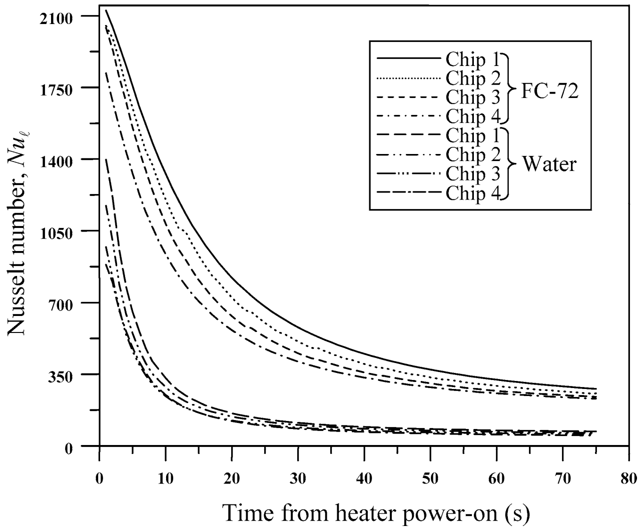

Fig. 6. Comparison of FC-72 cooling with water cooling.

7. Concluding remarks

Experiments have been performed using FC-72 to study the transient forced convection heat transfer from an array of four in-line, flush-mounted simulated chips in a vertical up-flow rectangular channel during power-on transient operation to determine the overall heat transfer coefficient. The effect of heat fluxes, geometric parameters such as chip configuration numbers are investigated and found that the heat transfer coefficient is affected strongly by the number of chips. The correlation equations are presented for four chips. The overall recommended correlation is given in Eq. (12), based on the present experimental conditions. Finally the comparison with water cooling studies are performed and the Nu_ℓ data found from FC-72 are similar to that from water and an overall increase of 70% in values is obtained by using FC-72.

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