Enhancement of heat transfer coefficients by actuation against an impinging jet

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Abstract

Recent technological developments have lead to significant increase in the generated heat by electronic and optical components. The removal of high heat fluxes can be successfully treated by several methods, e.g. impinging jets. Further improvement is offered by incorporating arrays of jets or causing jets to pulsate. The research reported herein introduces a new method which is based on actuation of a slab against a two dimensional steady, impinging, laminar, liquid micro-jet. This leads to enhanced heat transfer in the wall region of the jet. An experimental setup which included a piezoelectric (PZT) actuator, a dedicated silicon chip and a steady, slot, impinging jet, was assembled. Using a high speed infrared (IR) radiometer, the cooling process of the chip was recorded and the heat transfer enhancement values were determined for normalized actuation amplitudes, Reynolds and Strouhal numbers in the ranges of $0.45 < \delta < 0.75$, $756 < Re < 1260$ and $0 < St < 0.052$, respectively. It was experimentally found that heat transfer coefficients were enhanced by up to 34%.

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1. Introduction

1.1. Literature survey

Impinging-jet heat transfer has been thoroughly investigated because of their ability to efficiently remove heat from surfaces. Studies were performed on a wide range of applications (drying, annealing, heating and cooling), with circular or rectangular jets, free-surface or submerged, confined or unconfined and laminar or turbulent. Comprehensive summaries of these studies were reported by several investigators e.g. [1–10], who have observed that due to the thin thermal boundary layers developed in the stagnation area, elevated values of heat transfer were achieved. Nonetheless, the coefficients were reported to decay sharply through the wall jet region down to 1/5 (or lower) of the value at the stagnation point e.g. [11–13].

In order to further enhance average heat transfer coefficients (taking into account both stagnation and wall jet regions) a number of methods are available. Naturally, the most common is the integration of an array of impinging jets. Recent summaries of stagnation and average heat transfer coefficient correlations data base for arrays of jets were published by Webb and Ma [9] and Zuckerman and Lori [10]. The main drawback of this method is the need for increased fluid flow which leads to the use of larger and more energetic pumps. In order to increase the heat transfer, while maintaining low flow rates, pulsating jets were investigated. Several studies of turbulent pulsating jets e.g. [14–24] show that the time depended, sinusoidal, square or triangular pulsation profiles can effectively increase heat transfer coefficients. The enhancement was attributed to the intermittent build-up and breakdown of the hydrodynamic and thermal boundary layers caused by the pulsating jets. In contrast to the voluminous literature on turbulent jets, only a few studies on laminar pulsating jets were found e.g. [23,24] both of which were numerical. The investigators reported an increase of up to 20% in momentary heat transfer coefficients; however no significant increase in time averaged heat transfer was shown.

The present study presents an innovative approach for the increase in convection coefficient for a laminar jet in a confined configuration. It will be shown that the introduction of a reciprocating motion (actuation), perpendicular to a steady flow of an impinging jet, leads to the enhancement of heat transfer down the wall jet region.

In order to choose the implementation method of the reciprocating motion, a comprehensive literature review was conducted on available actuation methods [25]. Different actuators classifications are available according to their application technology, purpose, surrounding fluid, actuation direction, active or passive implementation etc. Most of the references found were for actuators effect on turbulent hydrodynamic boundary layers management, aimed at the reduction of the drag of air flows on wings e.g. [26,27]. Only a few investigations on the effect of actuation on heat transfer are available [28–36], dealing with air as the working fluid. The investigations reported in [28–30] dealt with passive methods, while active methods were reported in [31–36]. Of specific interest is the research reported in [33,34,36] in which piezo-electric devices (vibrating beams and piezo-electric driven...
synthetic jets) were implemented. The advantages of piezo-electric actuators are their ability of performing actuation of a few hundred microns, at a few hundred Hz while withstanding large forces with no limitation on the fluid medium. Therefore, it was decided to implement this method in the current study.

1.2. Hydrodynamic analysis

Fig. 1 shows the schematic stream lines for a laminar two dimensional fluid flow through a setup similar to the experimental setup detailed in this paper. The coolant micro-jet exits the top plane and flows towards the bottom one. The jet impinges at the stagnation point right below the jet exit nozzle. At this point the velocity and the thermal boundary layers are at their thinnest along the channel. Accordingly, the highest heat transfer coefficient is experienced at the stagnation region and sharply decays downstream to values as low as a fifth along the wall jet region. Further decrease is evident when the flow reaches a fully developed profile down the channel. Hence, the effect of the high heat transfer coefficient is usually confined to a significantly narrow area near the stagnation point, i.e. $0 < x/w < 2–3$, as reported in previous literature surveys e.g. [11–13].

The current research is based on the following premise: the basic flow configuration is kept, i.e. the coolant jet exits the nozzle at the top plane, impinges below and is diverted to flow through a micro channel of 200 $\mu$m height. In order to increase the average heat transfer down the wall jet flow region, we propose replacing the stagnation area by a slab (see Fig. 2) which can perform actuation against the impinging jet at various amplitudes (0–150 $\mu$m) and frequencies (0–400 Hz). A numerical analysis of the actuation effected flow regimes was performed, fully detailed in [25] and briefly summarized in the following paragraph. When the actuator is at its lowest position its tip is level with the bottom surface. During the ascension process, the distance between the slab tip and the upper surface diminishes, the jet impinges on the slab at a higher location, and the flow is deflected to the sides with increased average velocity, because of the constant flow rate. Throughout the ascending process a vortex is created beside the slab. As a result of the continuous ascending process, the vortex size and average velocity at the vortex boundary increases monotonically until the slab tip reaches its highest location, i.e. $l = l_{act}$ (see Fig. 2). At this point the vorticity is at its maximum. As could also be seen in Fig. 2, the vortex by the side of the actuator, combined with the deflected flow, may induce the creation of additional vortices downstream, at the top and bottom surfaces. Next, the slab begins its monotonic descend, inducing a counter flow at its side walls, hence detaching the vortex from the slab wall, and allowing the deflected jet to advance the vortex downstream. The axial and angular motion of the vortices is accompanied by a vorticity drop (due to internal and external fluid viscous forces) until the vortex vanishes and a standard laminar flow profile is developed in the micro-channel.

When the actuation frequency is increased, the vortex creation rate is increased as well; therefore a larger number of vortices are flushing the surface during any period of time. In addition, when the actuation amplitude is raised, the average deflected velocity

![Fig. 1. Characteristics of flow for a jet impinging on a flat surface.](image1)

![Fig. 2. Characteristics of flow for a jet impinging on an actuating slab.](image2)
is increased as well (due to the constant flow rate) hence contributing to enhanced vorticity.

Following the analysis above, an enhancement in heat transfer down the flow is expected by the increase in actuation frequency and/or amplitude.

2. Experimental setup

The experimental setup was designed to allow actuation at a variety of amplitudes and frequencies against a steady flow of the impinging liquid jet. The interaction between the actuator and the constant flow jet brings upon the creation of vortices and their motion down the flow while cooling the chip to the jet inlet temperature. This cooling process was measured by a high speed IR camera and the measured data was then processed to yield the heat transfer coefficient. Fig. 3 schematically describes the mechanical parts of the experimental setup, which is divided into five sub-systems according to the labels in these figures and which is described below. The fluid inlet is the first subsystem which is assembled of the following five components:

1.1 An injection pump (not shown), enables continuous fluid flow rates of 90–150 cc/min using two 60 cc syringes.
1.2 Polypropylene tubing (see Fig. 8) delivering the pumped fluid to:
1.3 The inlet fluid collector (1a).
1.4 The fluid is then passed through a transition adapter (1b) and finally to:
1.5 A S.S. 304 adapter (1c), which includes at its base a 220 µm wide, 500 µm deep and 6000 µm long micro through slot, manufactured by a precise laser drill. This slot allows the creation of a micro jet to be impinged on a micro actuator (5) creating vortices that propagate downstream and enhance heat transfer from the chip test surface (4).

2. The setup base and support plates were manufactured of PEEK (Poly Ether Ether Ketone) material, which can be readily machined and is resistant to a wide range of chemicals at the expected temperature levels. All sub-systems were attached to this base.

2.1 Fig. 4 shows a cross section view through the base plate (2a in Figs. 3 and 4). The base has, on both its faces, grooves for O-rings that seal the experimental setup in the assembled mode. On its bottom face, the base included a 200 µm high and 7000 µm wide groove. Together with the test chip (part 4 in Fig. 3 and picture in Fig. 6), the groove creates a micro-channel that, in an assembled mode, funneled the fluid from the jet outlet to the system outlet.

2.2 In an assembled mode, the chip support plate (2b in Fig. 3) was attached to the base and fixed the position of the test chip (4 in Fig. 3) relative to the base. In addition to a 15 mm × 15 mm window exposing the chip’s surface to an IR camera, the support plate also included, similar to the base, grooves for sealing O-rings.

3. The 3rd subassembly contains the exit collectors (3 in Fig. 3) that channeled the fluid from the setup exit through additional polypropylene tubing to the collector tank for future reuse.

4. The test chip (4 in Fig. 3, gray layer in Figs. 5–7) was manufactured of a 4”, 300 µm, 100 orientation Si slice at the RBNI Technion microelectronics center.

4.1 A picture of the experimental chip and the schematic description of areas of interest are shown in Fig. 6. The manufacturing process, which contains 22 steps, involves numerous materials and techniques, and is described in details in [25]. Only a few essential steps will be pointed out here.

4.1.1 Following several preparation processes, two electrical serpentine heaters and contact pads were sputtered using an E-beam evaporator on the chip’s top surface.
Next a through slot was manufactured at the center of the chip. Using several photo resist processes, combined with double sided mask exposures and a DRIE process, a 300 μm deep, 500 μm wide and 6500 μm long slot was manufactured. The slot was located between the two heating resistors described above (Section 4.1.1), and allowed the insertion of the actuation slab tip through the chip and in front of the jet exit.

Finally, the process described above (Section 4.1.2) was also used to cut the test chip into its final dimensions: 25.4 mm × 25.4 mm.

The 5th sub-assembly includes several parts:

The APA-200M actuator (5a in Fig. 3) is a mechanically enhanced PZT (Lead Zirconate Titanate) actuator, manufactured by CEDRAT (France). The actuator’s maximal amplitude of 230 μm is achieved at the resonance frequency of 900 Hz. However, in order to work in a safe actuation zone, the experiments were performed at actuations up to 150 μm and 400 Hz. In order to deliver the needed actuation against the steady jet, an actuation slab (5b in Figs. 3 and 7) was manufactured and attached to the top surface of the actuator. Additional equipment, discussed below, enabled the actuator activation.
5.2 The actuation slab (5b in Figs. 3, 5 and 7) was manufactured with width and length of 480 and 6400 μm, respectively. Precise dimensions of the slab were needed to allow, on one hand, the continuous motion of the slab through the slot on the chip, while leaving a minimal gap to minimize fluid leakage, on the other hand.

5.3 Nonetheless, due to the cooling liquid hydraulic properties, the minimal gaps were not sufficient to eliminate the leakage. The leakage was finally prevented by applying a sealer between the chip and the actuation slab as seen in Figs. 5 and 7. The only connection between the actuation slab and the chip was through the thin sealer. Several sealers were tested and finally an RTV was chosen.

5.4 The actuator base was attached to a XYZ linear stage with a positioning accuracy of <1 μm (see stage in Fig. 8). This stage allowed the precise positioning of the actuator tip through the slot in the chip while maintaining actuation at levels of 0–150 μm above the chip surface.

Heat transfer removal from the test chip was considered by several cooling liquids. Because of the required application of a sealant, the heater to sealant direct contact was not recommended, therefore the heater was applied on the top surface of the chip (in contact with the cooling liquid) while the sealant was applied on the bottom surface (in contact with the actuator side wall). In order to allow proper function of the heaters while being in direct contact with the cooling liquid (avoiding short-circuit), the most important property of the fluid was its dielectric constant. Several coolants were considered: purified/de-ionized water and Fluorocarbons coolants that are widely used in industry.

(a) Purified and de-ionized water were tested; however the water chemical property (absence of ions) led to chemical corrosion of the non-coated heaters. Therefore, these liquids were unsuitable.

(b) Due to the fluorocarbons coolants inert chemical property and their elevated dielectric constant, the FC-3283 Fluorinert coolant was finally chosen. The fluid properties are given in [37].

Measurement apparatus, data loggers and additional electric peripheral equipment:

(a) The inlet and outlet fluid temperatures were measured using T type thermocouples which were sampled at 50 Hz by a data logger. The measurement accuracy of the thermocouples was estimated as 0.5 °C, and the nominal accuracy of the sampler was 0.5 °C.

(b) In order to drive the actuator, a sinusoidal signal was generated by an analog signal function generator in the 0–10 V and 0–400 Hz ranges. The signal was amplified by 20 folds using a linear amplifier and was used as the input signal for the APA-200M actuator.

(c) In order to measure the actuation height, strain-gages were assembled on the actuator mechanical amplifying structure. The strain-gage signals were sampled by a conditioner and the uni-polar (0–10 V) conditioner output signal was sampled by an additional high-speed data logger. Because of strain-gages location, they did not measure the actual actuation; however the measured signal was linearly coupled with the actual actuation. In a preparation process a calibration curve (μm vs. voltage) was produced.

(d) The chip surface temperature was measured by a high speed, MWIR (3–5.2 μm) IR camera. The camera has a full frame 240 × 320 pixels InSb sensor, cryo cooled at 71 K, capable of measuring in the full frame mode at up to 180 Hz. The typical NETD of the camera is 0.025 K (@300 K) and using a black body calibrator, an accuracy of less than 2 K (typically 1 K) was achieved in the range of 20–125 °C. In order to examine the effect of actuation frequency at up to 400 Hz, the sampling rate of at least 800 Hz was required. This frequency was achieved by narrowing the IR camera sampled frame down to 1/10 of the full frame, i.e. 64 × 120 pixels. Using the 1G magnifying lens, a typical 1.9 mm × 3.6 mm window was sampled at the elevated frequency. Additional decrease in measurement error was achieved by coating the chip surface with a black diffusive paint layer with an emissive factor of approximately 0.95 [38].

A detailed uncertainty analysis was performed to account for possible error sources using the method outlined by Moffat [39]. Considering the measured data uncertainties, the maximal uncertainties of the cooling process time constant (τ) and the heat transfer enhancement (ε – derived from the time constant – see Section 4) were 7.8% and 12.9% respectively. Taking into account the uncertainty of the extraction method (5.8%, see method in Appendix B) leads to a maximal overall uncertainty in heat transfer enhancement of 14.2%.

3. Experimental procedure

Preliminary experiments were done with several mass flow rates without actuation, keeping the actuator slab tip surface level with the chip surface. These experiments were performed in order to obtain reference data for the calculation of the heat transfer enhancement at various actuation amplitudes and frequencies. Listed below are the experimental stages for both reference and actuation experiments:

3.1 The actuation system was set at the required amplitude and frequency levels, followed by the initiation of the actuation parameters sampling system. Specifically, the signal generator output signals were sampled prior to the linear amplifier, due to measurement equipment limitations. The actuation profile was set as sinusoidal in order to avoid a premature

![Fig. 8. Side view of the experimental setup. The IR camera (located above the experimental setup) is not shown in this figure.](image-url)
failure of the PZT actuator. A premature failure could be initiated by a sharp gradient input command, which could lead to the failure of the glue connecting the array of PZT panels in the actuator stack. In addition, the calibrated strain-gauge (mounted on the actuator) data was also measured to receive full reconstruction of actual actuation profile.

3.2 Next, the liquid pump was started at a chosen flow rate followed by the initiation of inlet/outlet temperatures sampling system.

3.3 Then, the power supply to the heater on the chip was initiated in order to increase the temperature on the chip to a required level. Relatively high temperatures were required in order to obtain a large number of samples during the characterization of the cooling process, while still keeping a safe temperature difference below the boiling temperature. This safe range was needed to minimize gas contents in the fluid and for the characterization of the single phase heat transfer mechanism.

3.4 Following a short stabilization period, the IR camera data sampling software was initiated. During the sampling period a continuous flow of liquid at constant inlet conditions was maintained through the experimental setup.

3.5 Next the power to the heater was stopped, and the cooling process, effected by flow rate, actuation amplitude and frequency levels, was recorded.

3.6 Following the short cooling process of the chip and the exhaustion of most of the liquid in the pump syringes, the pump together with all sampling apparatus were stopped as well.

3.7 All data files (IR camera, input/output temperatures signal generator and strain-gauges data) were saved.

4. Data reduction

Prior to the description of the analysis procedure, a few details should be noted:

(a) Due to experimental limitations (IR radiometer window width, actuator width and sealing spread on the chip) only the data for the wall jet region 3.6 < x/w < 10.0 (0.8 < x < 2.2 mm from jet centerline) was considered.
(b) The data presented hereafter is of the chip center line (symmetry is assumed).
(c) In order to investigate actuation frequency and amplitude effects the measured data was spatially averaged along the chip centerline.

4.1 The extraction of the heat transfer enhancement data was done by treating the volume of interest (based on the region of interest detailed above) as a lumped capacitance system. Assuming no internal heat is applied, the temperature response of such a system to external conditions is [40]:

\[
T(t) = T_{\text{ref}} + \left( T_{\text{ini}} - T_{\text{ref}} \right) \cdot \exp(-t/\tau)
\]

In Eq. (1) T(t) and T_{\text{ini}} are the time depended and initial system temperatures, measured with the IR radiometer. T_{\text{ref}} is the reference temperature, measured at the system inlet with thermocouples, t is the time and \( \tau \) is the system time constant. Since the response of the chip to the fluid heat transfer coefficient is of interest, while excluding other ambient effects, only the initial cool down process should be taken into account, i.e. \( t < 1/2\tau \). First order evaluations of the expected time constant and additional elaborations are detailed in Appendix A. An example of the measured temperatures can be seen in Appendix B (Fig. 21) and an example of the chip centerline temperature distribution at several time steps, for actuation amplitude of 150 \( \mu \)m, frequency of 325 Hz and flow rate of 150 cc/min (Re_{in} = 1260) is shown in Table 2. As mentioned earlier, only the wall jet region (3.6 < x/w < 10.0) temperature profile was processed – see green line in Table 2. Based on Eq. (1) and measured temperatures, the time constant during each cooling process was subtracted – see details in Appendix B. Finally, using the time constants the heat transfer enhancement was calculated based on the following definition:

\[
\varepsilon = \left( \frac{\tau_{\varepsilon}/\tau - 1}{h/h_{0} - 1} \right) \cdot 100 \quad [\%]
\]

where \( \tau \) is the cooling process time constant, depended on the flow rate and actuation amplitude and frequency, and \( \tau_{\varepsilon} \) is the cooling process time constant at the same flow rate without actuation (\( f = 0 \text{ Hz} \)) where the actuator slab tip is leveled with the chip surface.

4.2 In order to validate the post-processing method detailed in Appendix B, a simplified numerical simulation was prepared. A symmetry quarter of the original chip was simulated using a conductor–capacitor (G-C) network representation. The chip was represented by nearly one hundred nodes while the environment was represented by a few other diffusive (chip holder) or boundary (fluid) nodes. A schematic descript-
tion can be seen in Fig. 9. Similar to the experimental setup, the silicon 1/4 chip dimensions were 12.7 × 12.7 × 0.3 mm$^3$. The holder material was PEEK which was in contact with the chip on three areas (A1, A2 and A3) as depicted in Fig. 9. Similar to the experiments, the chip was pre-heated on area A4 to reach steady state temperature, and a non-uniform heat transfer coefficient was applied on the remaining free area. The heat transfer coefficient was determined using the correlation recommended by Wadsworth and Mudawar [41] of the form:

$$\text{Nu}_x = \frac{\text{Re}_w^{0.5} \text{Pr}^{1/3}}{} \left[ \left( \frac{\text{Nu}_x}{\text{Re}_w^{0.5}} \right)^{1/5} + \left( \frac{\text{Nu}_x}{\text{Re}_w^{0.5}} \right)^{-1/5} \right]$$

(3)

where the S subscript stands for the stagnation region correlation suggested by Wadsworth and Mudawar and the $P$ subscript stands for the Pohlhausen's flat plane solution for the wall jet region (for more details see [41]). The calculated heat transfer coefficient profile is depicted in Fig. 10 for $Re = 630$ and 1260. Fig. 11 shows the steady state temperature distribution of the simulated chip, and Fig. 12 shows the transient cooling process simulation results for $t > 0$ (in the absence of the applied heat) in steps of 0.02 s (initial steady state distribution is at $t = 0$ s). Note that the peak temperature at $t = 0$ is received at the upper left corner of the chip (chip center) where the heat is applied, even though that area experiences the highest heat transfer coefficients (see Fig. 10). The elevated heat transfer coefficients around the chip center are evidenced during later stages where a meaningful drop in temperature occurs at the same location.

In order to evaluate the heat transfer enhancement, the average temperature of the chip center-line in the vicinity of the heater i.e. $5 < x/w < 10$ (see purple lines in Figs. 9 and 11) was reduced as a function of time, similar to the experimental procedure. The two temperature profiles for $Re = 630$ and $Re = 1260$ are shown in

Fig. 11. Chip initial temperature map ($t = 0$ s) for $Re$ number 630 (simulation results).

Fig. 12. Chip transient temperature maps (0–0.06 s) for $Re$ number 630 (simulation results).
The applied average heat transfer coefficient in that area was 2303 W/m²K for $Re = 630$ and 3257 W/m²K for $Re = 1260$, giving an enhancement ratio of $e = 1.41$ (due to $h \propto Re^{0.5}$). The post-process described in Appendix B was applied to the numerically obtained temperature profiles. The results detailed in Table 1 show a post-process error of about 4% when processing the first 60 data points (Case 1) and an error of about 7% when processing the following 60 data points (Case 2). The errors are attributed to heat conduction – the results for the analysis for a chip with a zero heat conduction coefficient show a zero post-process error (Case 3 in Table 1). It should be noted that this method allows the calculation of heat transfer enhancement ratio, however it does not allow a correct calculation of the heat transfer coefficients (could theoretically be subtracted from $\tau$). About the same error is anticipated for the experimental post-process, which was previously elaborated.

### Table 1
processed results for numerical temperature profiles.

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<th>Case</th>
<th>Data points</th>
<th>Time range (s)</th>
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<th>$e_{theoretic}$</th>
<th>Error (%)</th>
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<td>0–0.06</td>
<td>1.41</td>
<td></td>
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</tr>
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</table>

### Table 2
Chip cooling process for actuation of $f = 325$ Hz and $Amp = 150$ μm.

5. Results and discussion

In order to present the experimental results, some non-dimensional groups are defined: the Reynolds number $Re = (v_{in} \cdot w)/\nu$, where $v_{in}$ is the inlet average velocity, $w$ is the width of the jet nozzle and $v$ is the coolant kinematic viscosity. Delta $\delta = \frac{\Delta x}{H}$, where $\Delta x$ is the actuation amplitude and $H$ (a constant) is the micro-channel height. The basic Strohal number definition is $St = (f \cdot L)/v_{in}$ where $f$ is the actuation frequency and $L$ is a characteristic length. The St number is defined as the ratio between the inertial force induced by the actuation to the inertial force of the coolant jet. High values of $St$ imply strong actuation effect on the fluid flow. Since the dimensions of the micro-channel are constant, the characteris-
tic length can be taken as the distance between the jet exit and the opposite wall – i.e. the chip upper surface (the channel height). Thus, \( St = (f \cdot H)/v_{in} \), where \( H \) is constant. However, in our case, the distance between the jet exit and the opposite surface is actuation amplitude dependent, therefore the \( St \) number is redefined to account for the actuation amplitude, i.e. \( St_{act} = (f \cdot H)/v_{in} \cdot \delta = (f \cdot l_{act})/v_{in} \). This definition of \( St \) number takes into account all effects: flow rate, actuation frequency and actuation amplitude.

The experiments reported here were carried out at mass flow rates of 90–150 cc/min, i.e. \( Re_{in} = 756–1260 \). The actuation parameters were: amplitude – 90–150 \( \mu \)m, i.e. \( \delta = l_{act}/200 \) in the range of 0.45–0.075; and frequencies in the range of 0–400 Hz, namely \( St_{act} \) range of 0.0–0.052.

5.1. Heat transfer enhancement at constant \( \delta \) depended on different parameters

Figs. 14–16 depict the dependence of convective heat transfer enhancement (\( \varepsilon \)) at several \( \delta \) numbers (results for each \( \delta \) are depicted in a separate figure), for a range of \( St_{act} \) and \( Re_{in} \) numbers.

Since \( \delta \) is fixed, the change in \( St_{act} \) in these figures is due to the change in the actuation frequency only. In general, at fixed \( \delta \) and \( Re \) numbers, a monotonic increase in \( \varepsilon \) is observed. Moreover, at \( St_{act} < 0.01 \) a linear dependency of \( \varepsilon \) on \( St_{act} \) is observed in all cases. This trend can be explained by the enhancement in actuation frequency, hence the increase in the rate at which vortices are created. In turn, the increase in the number of vortices per unit time, flushing the cooled surface, leads to the enhancement in heat transfer coefficients. At given \( \delta \) and \( St_{act} \) numbers, an increase in \( Re \) number leads to the enhancement of average deflected fluid velocity flowing above the reciprocating slab. Hence, the angular velocity of the vortex created at the slab side walls increases as well, followed again by an enhancement in heat transfer coefficients at the cooled surface.

In the range 0.01 < \( St_{act} < 0.025 \) a decrease in the slope of the curves was noted, down to zero (\( \varepsilon \) was kept constant) at the lowest \( Re \) and \( \delta \) values (756 and 0.45, respectively). At these conditions a critical actuation frequency is observed, for which a further increase in frequency does not cause a change in \( \varepsilon \) values. Under these conditions, any heat transfer enhancement was achieved only by the increase in actuation amplitude rather than its frequency. This phenomenon may be explained by a complicated 3D flow that caused the formation of “Vortex Pairing”. The pairing phenomenon was previously reported by Wygnanski and Petersen [42] and Greenblatt and Wygnanski [43]. They demonstrated that disturbances in a range of \( St \) numbers cause the creation of vortex pairs between two fluids in contact, flowing at different velocities. The investigators disclosed that at an intermediate \( St \) range, the disturbances stabilized flow phenomena while disturbances at levels above or below that range caused enhancement flow phenomena. The different affects were attributed to Kelvin–Helmholtz instability.

In contrast to the stabilizing effect at low \( Re \) numbers, a renewal of heat transfer enhancement was revealed at higher \( Re \) numbers for \( St_{act} > 0.025 \). An increase in heat transfer enhancement of up to 34% was established at \( Re = 1260 \), \( \delta = 0.75 \) and \( St_{act} = 0.032 \). For intermediate values of \( Re \) and \( \delta \), a mixture of the described phenomena was noted.

5.2. Heat transfer enhancement at constant \( Re \) depended on different parameters

In order to further analyze the frequency-actuation related enhancement phenomenon, the data are re-plotted in
Figs. 17–19, at constant \( \text{Re} \) numbers and varying \( \delta \) numbers. These figures reveal that in the \( \text{St}_{\text{act}} > 0.025 \) range, all curves merge into a single curve in each figure. Due to the new definition of \( \text{St}_{\text{act}} \) number, the merging of the data into a single line alludes to similarity in \( \delta \) in the specified range. Nevertheless, in order to fully validate this conclusion, additional experiments should be performed for \( \text{St}_{\text{act}}/C_29 \). In order to elucidate the dependence of \( \epsilon \) on \( \delta \), Fig. 20 shows the same data depicted as in Fig. 19, however \( \epsilon \) is presented as a function of \( \text{St} \) in its original definition. As can be clearly observed, a major effect of \( \delta \) (or \( l_{\text{act}} \)) on heat transfer enhancement is evident throughout the entire \( \text{St} \) range. The change in actuation heights causes an increase in the average flow velocity because of the decrease in cross-sectional area. Following, the angular velocity of the vortices increases, leading again to the enhancement in heat transfer coefficients at the cooled surface. Finally, no evidence of similarity in \( \text{Re} \) was found.

6. Summary

The increase in the heat transfer coefficients of a two dimensional, laminar, liquid impinging jet was investigated experimentally. The stagnation zone of the impinging jet was replaced by a slot, through which a slab was actuated against the steady flowing jet. The deflected jet created vortices down the flow, which flushed the surface. The actuation amplitudes, frequencies and flow rates of up to 150 \( \mu \)m, 400 Hz and 150 cc/min, respectively, defined a Strouhal numbers of up to 0.052. Under these conditions, a maximal effective increase in the heat transfer coefficients down the wall jet region of 34\% was observed for \( \text{Re}_{\text{in}} = 1260 \) and \( \text{St}_{\text{act}} = 0.032 \). The increase in heat transfer coefficients is attributed to the actuation process that creates vortices that repeatedly flush the cooled surface, to the buildup and breakdown of the boundary layers and to the increase in the mixing process between the thin boundary layers and the bulk fluid.

Appendix A

When the chip is in contact with its surroundings (in addition to the cooling fluid), the surroundings contribution to the chip response is dependent on the contact quality, dimensions and thermal and physical properties of the materials. This kind of interaction is difficult to assess unless the contact quality is accurately known or experimentally calibrated. However, assuming that
the volume of interest is a lumped capacitance system, and only the initial cooling process is considered, i.e. $t < 1/2\tau$, it can be assumed that the volume response in that period of time is isolated from ambient effects, other than the interaction with the fluid. Based on Eq. (1) the time constant is $\tau = (m \cdot C_p)/(h \cdot A) = (V/A) \cdot (p \cdot C_p/h) = L/C_0$, where $L$ is the characteristic length, $p$ is the chip density ($2330 \text{ kg m}^{-3}$), $C_p$ is the chip heat capacity ($812 \text{ J kg}^{-1} \text{ K}^{-1}$) and $h$ is the approximated heat transfer coefficient ($\approx 3000 \text{ W m}^{-2} \text{ K}^{-1}$). The chip characteristic length is defined as $L = V/A = (25.1 \cdot 25.1 \cdot 0.3 \cdot 10^{-9})/(25.1 \cdot 7.0 \cdot 10^{-6}) = 1.1 \cdot 10^{-3} \text{ m}$. It should be noted that only about 14% of the chip’s surface is in contact with the cooling fluid. Therefore, if only the volume in contact with the fluid is of interest (in the vicinity of chip center line), the characteristic length is $L_c = V/A = (25.1 \cdot 7.0 \cdot 0.3 \cdot 10^{-9})/(25.1 \cdot 7.0 \cdot 10^{-6}) = 0.3 \text{ mm}$. Substitution of dimensions and properties gives $0.2 < \tau < 0.7 \text{ s}$.

Appendix B

In order to determine the heat transfer enhancements dependence on the flow rate and actuation parameters a MATLAB™ code was written:

(a) First, the measured inlet and outlet coolant temperatures (Fig. 21a) are imported. The outlet temperature is differentiated in time in order to find and mark down the moment of chip power shut down. Using the time mark, the coolant inlet temperature is subtracted and assigned as the reference temperature ($T_{\text{ref}}$ in Eq. (1)).

(b) Following, the chip IR temperature data is imported (Fig. 21b). The power shut down is marked (again by using differentiated data) and the initial temperature ($T_{\text{ini}}$) in Eq. (1) is subtracted.

(c) Next, a best fitting process is applied to the IR measured data using the Least Square method of the Matlab™ Curve Fitting Toolbox™ and Eq. (1) – see Fig. 22. This step is finalized by the subtraction the time constant supplied by the Curve Fitting Toolbox.

(d) Finally, the time constant is used to determine the heat transfer enhancement as defined by Eq. (2).

Data in Figs. 21 and 22 are for actuation amplitude and frequency of 150 $\mu\text{m}$ and 325 Hz respectfully and $Re = 1260$.

References


