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Jet impingement cooling using fluidic oscillators: an experimental study

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Abstract. A growing portion of the thermal load on board airplanes is due to densely packed electronic systems. This increased thermal load along with constraints on weight and volume have made simple and reliable cooling solutions an urgent need in the aerospace industry. There is a wealth of cooling solutions available in order to meet these demands, the simplest and most adaptable of which is probably jet impingement cooling. In this study, fluidic oscillators capable of producing pulsating jets were used to cool a heated surface and were then compared to equivalent steady jets. Although pulsating jets can be produced using a number of devices, fluidic oscillators offer the advantage of not having any moving parts. These oscillators are sustained by a self-induced internal flow instability and can function at different scales. Although the major part of this work is based on prototypes that produce jets with sub-millimetric widths, designs at one tenth that scale, i.e. with an exit slot width of 50 μm , are also presented. Reynolds numbers ranging from $\text{Re}_D = 3500$ to 5250 and jet-to-plate spacing from $1D$ to $10D$ were studied (where D is the initial width of the jet). The Nusselt number distribution is found for each case and a comparison is made between the performance of equivalent steady and pulsating jets based on the average Nusselt number.

1. Introduction

In the aerospace industry, electrical actuation is superseding hydraulic systems at an increasing rate. An example of this can be seen in Airbus' A380, where the thrust reversers are electrically actuated instead of relying on hydraulic devices. Furthermore, constraints on weight and volume favor highly integrated control and power electronic systems that, as a consequence, produce high density heat fluxes. If not managed properly, they can lead to a malfunction in the components and can damage the circuits (degradation of bonding wires, delamination of solders in power modules) and the supporting structures, thus threatening the safety of people on board. The literature offers a wealth of cooling solutions that can address this issue. They range from single-phase systems, involving, for instance, spray cooling, to two-phase systems employing Phase Changing Materials (PCM). Among these cooling systems, impinging jets seem to be the only solution that offers a reasonable compromise between simplicity, adaptability and relatively high heat transfer coefficients. Impinging jets can be used to either directly cool the heat sources or to remove heat from the surfaces of heat exchangers. Some of the earliest attempts to enhance jet impingement cooling by using pulsating jets can be found in the works of Burmeister [1] and



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Nevins and Ball [2]. Cochrane and Nevins [3] even attempted to visualize a pulsating jet as it impinged on a heated surface. Since then, numerous studies were undertaken to verify under what conditions, if any, it is possible to improve heat transfer using pulsating jets.

When periodic perturbations are introduced into the flow, two main effects can occur. First, the pulsations can either amplify or suppress flow instabilities that can interact with the heated surface ([4]). And second, the unsteadiness of the flow interferes with the growth of the thermal boundary layer in the wall jet region ([5] [6]). However, by surveying the literature, it is difficult to pinpoint the exact combination of parameters that can consistently improve heat transfer. The main parameters in a pulsating impinging jet are the shape of the nozzle (circular or slot jet), the nozzle-to-plate distance (or standoff distance), the Reynolds number, the pulsation frequency, waveform, amplitude and duty cycle, among many other factors.

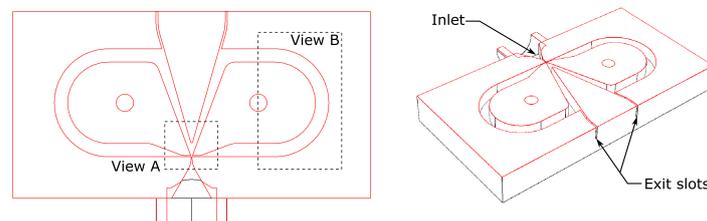


Figure 1. Plan (left) and perspective view of the pulsating jet oscillator.

Furthermore, there are a number of devices that produce pulsating jets, such as rotating valves ([7]), acoustic excitation ([8], [9]), and mass flow controllers ([10]). However, in a recent review on dynamic thermal management in the aerospace industry ([11]), the authors stressed the importance of simplified fluid feed systems, whereas all the above-mentioned techniques involve moving parts that require active control. As an alternative, the same authors suggest the use of fluidic oscillators that can produce unsteady jets from a self-induced instability. This phenomenon solely depends on the internal geometry of the device, so that no external control is needed to activate it. In the present study, a fluidic oscillator (Fig. 1) that produces pulsating jet is used instead of the well-known sweeping jet oscillators. The sweeping jet oscillator is usually used to delay flow separation on airplane wings ([12]). Sweeping impinging jets are capable of covering larger areas and result in an evenly distributed cooling rate. However, the spatial oscillation of the jet increases the production of turbulent kinetic energy in the space between the nozzle and the target surface, which accelerates its decay before impact. Zhou et al.[13] showed that this can decrease performance, in terms of heat transfer, compared to a steady jet having the same average mass flow rate. The inhomogeneous distribution of the thermal load also requires a solution capable of targeting specific components with dimensions of a few hundred microns or less. To the authors' knowledge, only two previous studies ([14], [15]) used pulsating jet oscillators in the same context considered here.

In what follows, the heat transfer performance of pulsating impinging jets produced by a fluidic oscillator are studied. The oscillator has a constant depth and the slot jets at its exit are 0.7 mm wide and pulsate at a frequency of around 1 kHz. A glass plate with an Indium Tin Oxide (ITO) coating is used as the heated target plate. A comparison is made between pulsating and steady jets having the same average mass flow rate and the same dimensions based on the average Nusselt number across the centerline of the heated surface.

2. Methodology

The oscillator presented in Figure 1 is based on an iteration of Warren's Negative Feedback Oscillator [16] that was characterized by Wang et al. [17]. The distinctive property of this design

that sets it apart from the pulsating jet oscillators used in [14] or [15], is its nearly constant frequency at inlet pressures higher than 3 bar. The prototype was made by stereolithography (more commonly known as 3D printing).

The method used to compute the forced convection coefficient h is well-known (e.g., see [8]) and is based on Newton's cooling law:

$$\phi_{c,osc} = h(T_{p,osc} - T_f) \quad (1)$$

The method consists of plotting the convective heat flux $\phi_{c,osc}$ at each point of interest as a function of the temperature $T_{p,osc}$. A linear regression of the data produces the slope h in Eq. 1, that goes into computing the Nusselt number $Nu = hL/k$, where L is a characteristic length of the convective flow, equal to the hydraulic diameter $D_h = 2D$, and k is the thermal conductivity of air. The temperature is measured using an infrared camera placed on the other side of the target plate. Due to the proximity of the oscillator to the impact plate, it was not possible to accurately capture the temperature field on the oscillator's side of the plate. The Biot number $Bi = h_{c,nat}e/k_{glass}$ along the thickness e of the glass plate and based on the appropriate natural convection coefficient $h_{c,nat}$, is less than 0.1 which supports the assumption that the average temperature is nearly the same from one side to the other. The appropriate corrections due to radiation heat fluxes and lateral heat losses were taken into account when computing the convective flux and the plate temperature (for the sake of brevity, the reader is referred to [8] for more details).

Finally, assuming that the Nusselt number is a function of n input parameters:

$$Nu = F(x_1, x_2, \dots, x_n) \quad (2)$$

the standard uncertainty was computed as follows:

$$\Delta Nu = \pm \left[\sum_{j=1}^n \left(\frac{\partial Nu}{\partial x_i} \Delta(x_i)^2 \right) \right]^{1/2} \quad (3)$$

3. Findings

A spatial average of the mean Nusselt number was computed between $x/D = -15$ to 15 for both the steady and pulsating jets. The average is plotted as a function of standoff distance H/D for two Reynolds numbers $Re_D = 3800$ and 5250 (Fig. 2 and 3). For both the pulsating and steady jets, there is a distinctive maximum at $H/D \simeq 4 - 5$, which roughly coincides with the tip of the potential core of the jets. In the steady case, the increase in the Nusselt number from small impact distance up to $H/D \simeq 4 - 5$ is explained by the increase of turbulence intensity along the jet axis while the velocity in the potential core remains to a large extent constant ([18]). When the potential core is completely eroded by mixing with the surrounding fluid, the velocity begins to rapidly decay, offsetting any increase in heat transfer due to the increase of turbulence intensity beyond the potential core. What is surprising in this case is that the same behavior is observed for the pulsating jets, albeit with higher values of the average Nusselt number for $H/D < 6$. Gardon and Akfirat [18] showed that, by increasing the initial turbulence intensity of the jet, the Nusselt number decreases monotonically with nozzle-to-plate distance. The same would have been expected for the pulsed impinging jets since the turbulence intensity increases by 8 to 18% (depending on the Reynolds number) along the jet axis compared to a steady jet with the same average mass flow rate (data not shown in the present paper). For $Re_D = 3800$, the average Nusselt number is nearly the same for both steady and pulsed cases at small standoff distances ($H/D < 5$). For larger distances, there is a drop off in performance for the pulsed jet. For this case, there is a small improvement from $H/D = 3$ as can be seen in Figure 4, however

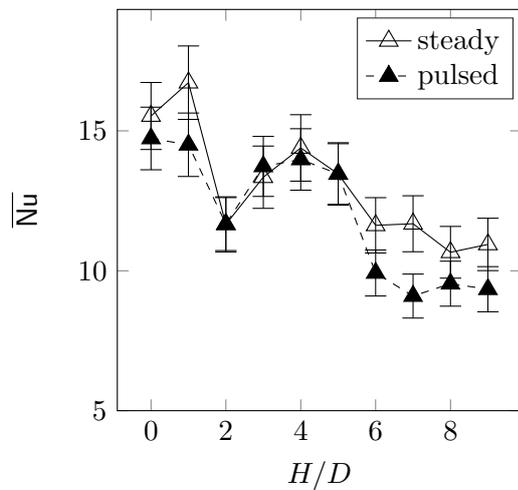


Figure 2. Average Nusselt number as a function of impact distance H/D at $Re_D = 3800$

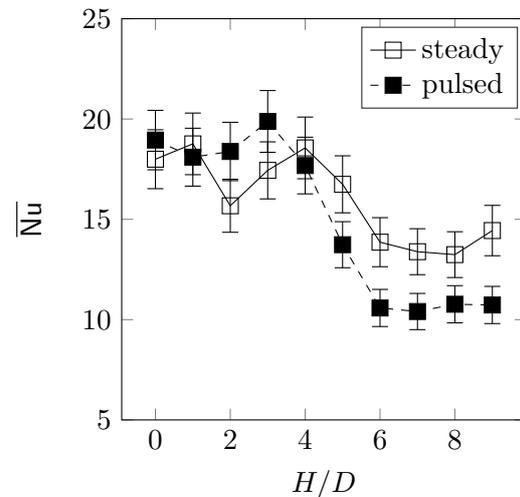


Figure 3. Average Nusselt number as a function of impact distance H/D at $Re_D = 5250$

this lies within the uncertainty bounds. For $Re_D = 5250$, pulsating the jets seems to improve heat transfer for $H/D < 4$ with a maximum enhancement of 15% in averaged Nusselt number for $H/D = 3$. This is due to an improvement in local Nusselt number around the stagnation (Figure 5).

Prototypes one tenth the scale of the model presented above were manufactured using the microfabrication facilities of the Renatech technological platform at the LAAS. The two prototypes shown in Figure 6, were made by dry-film deposition on silicon wafers, and produce micro-jets 50 μm wide. Using data from a microphone placed at the outlet of these oscillators, it was possible to observe a sharp peak in the spectral data that should correspond to the

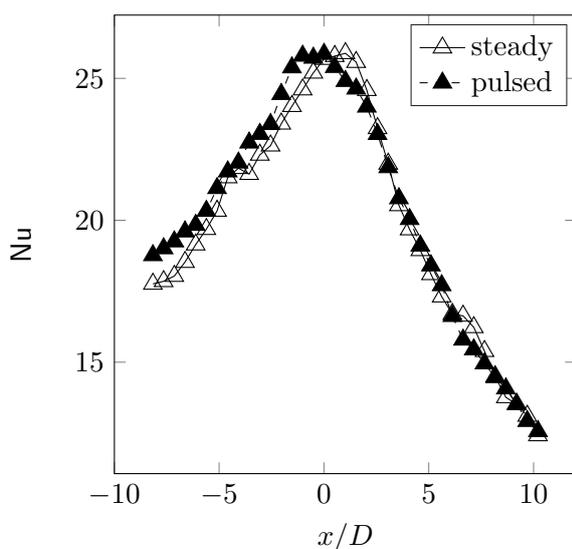


Figure 4. Nusselt number profile for $H/D = 3$ at $Re_D = 3800$

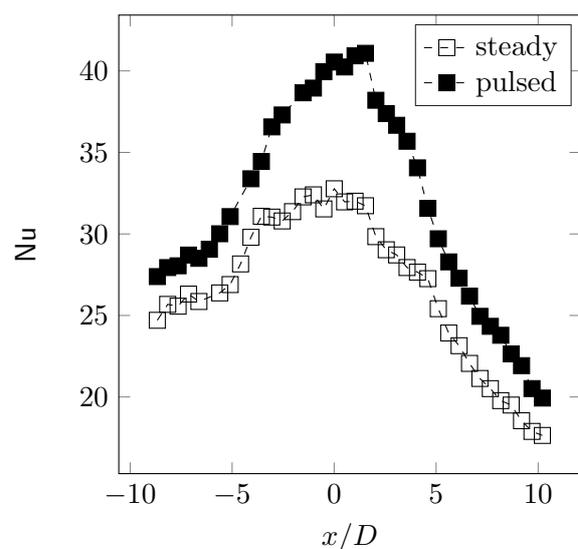


Figure 5. Nusselt number profile for $H/D = 3$ at $Re_D = 5250$

pulsation frequency. For the design presented in Figure 1 (at 1:10 scale), the peak corresponds to a frequency of around 8800 Hz, which is about 10 times larger than the frequency of the macroscopic design. This was expected, since the oscillation period is roughly proportional to the length of the feedback loop [17].

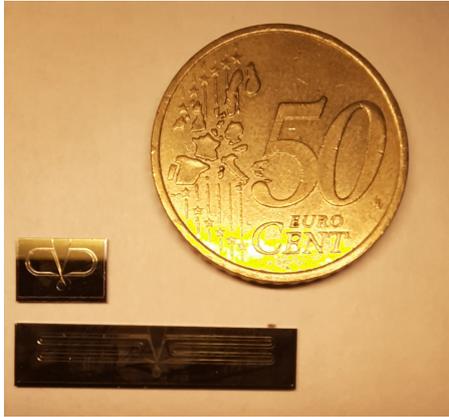


Figure 6. Two designs of the pulsating jet oscillator at one-tenth the scale used in the present study, made by dry-film deposition, with a 50-cent coin to give a sense of scale.

4. Conclusions and Perspectives

The aim of this study is to compare the heat transfer performance of steady and pulsating impinging jets. It was found that pulsating jets can improve performance significantly for relatively small nozzle-to-plate distances. A more comprehensive study is required in order to properly assess the effects of nozzle-to-plate distance, pulsation frequency and Reynolds number on the jet impingement heat transfer. In addition, an experimental campaign will be conducted on the micro-oscillators. A set of temperature sensors are going to be integrated onto a silicon substrate. Then the oscillator is formed by photolithography using a negative photoresist over the same substrate. This will allow us to monitor the flow inside the channels of the oscillator. Furthermore, a silicon wafer with an array of integrated temperature sensors is used as a target plate. Instantaneous Nusselt number distributions over the plate are then computed from the sensor data. Results obtained from the integrated temperature sensors will be presented during the conference.

Acknowledgments

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