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PULSED IMPINGING JETS PRODUCED BY FLUIDIC OSCILLATORS CAN IMPROVE HEAT TRANSFER

Georges C. Saliba[1,*], Vincent Raimbault[2], Rémi Gilblas[1], Lucien Baldas[1]

[1]Institut Clément Ader (ICA), Université de Toulouse, CNRS, INSA, ISAE-SUPAERO, Mines-Albi, UPS, Toulouse, France
[2]CNRS, LAAS, 7 Avenue du Colonel Roche, F-31400 Toulouse, France

ABSTRACT

Pulsed jet impingement was shown to enhance performance under specific conditions. However, there is no consensus in the literature on what those conditions are. In the present work, a fluidic oscillator is used to produce pulsed slot jets that impinge on a heated plate. Fluidic oscillators are self-excited devices requiring only a pressure source to function; in other words, they do not depend on any external control system or power source. In addition, they do not have any moving parts, which makes them an attractive solution for a number of applications such as flow control on airplance wings and heat transfer. The behavior of the oscillator is determined by a number of factors relating to both operating conditions, such as supply mass flow rate, and design parameters, such as feedback loop length and width. Some of these aspects are explored in the present work. With regards to jet impingement heat transfer, the impact of Reynolds number, pulsation frequency and standoff distance on performance is evaluated by computing the peak and average Nusselt number and comparing them to those of an equivalent steady jet. It was shown that pulsing the jet improves heat transfer (sometimes by up to 40%), especially for shorter standoff distances and higher Reynolds number. Applications where a compact cooling solution is needed can take advantage of these conclusions as well as the simplicity and robustness of the fluidic oscillator.

1 INTRODUCTION

Jet impingement is one of the simplest and most effective methods of exchanging heat between a fluid and a solid surface. For this reason, it has found its way into a variety of applications from cooling turbine blades to heat management for electronic systems. The effectiveness of jet impingement cooling lies in their ability to thin out the thermal boundary layer in the stagnation region of the flow, allowing for a direct contact between the cold fluid and the heated surface. Outside this region, the thermal boundary layer reappears and continues to grow in the downstream direction leading to a rapid decrease in heat transfer. As early as 1959, researchers have attempted to improve impingement cooling by introducing periodic perturbations into the jet which would both alter the dynamics of the flow and affect the growth of the thermal boundary layer. Unlike other parameters such as the distance between the jet orifice and the target surface or the Reynolds, the effects of the pulsation parameters, i.e., frequency, amplitude and waveform, remain inconsistent across studies. With these additional parameters, it becomes difficult to dissociate the effect of each parameter on heat transfer.

Furthermore, there is a variety of pulsed jet actuators that are available to the experimenter with different operating principles. Most of these devices rely on mechanical or acoustical actuation, such as a piston/cylinder assembly, a rotating valve or a vibrating membrane and require an external control system and a constant power supply. In addition, moving parts are subject to wear over time and in some situations replacement and maintenance costs can be prohibitive. The field of fluidics offers a no-moving-parts alternative: the fluidic oscillator. Fluidic devices were competitors of electronic circuits in the early fifties and consisted of pneumatic channels capable of performing computational tasks. One of the main advantages of fluidics over electronics at that time was the robustness of the devices and the fact that they did not dissipate heat and so did not require cooling. Electronics eventually superseded

*Corresponding author: georges.saliba@univ-tlse3.fr

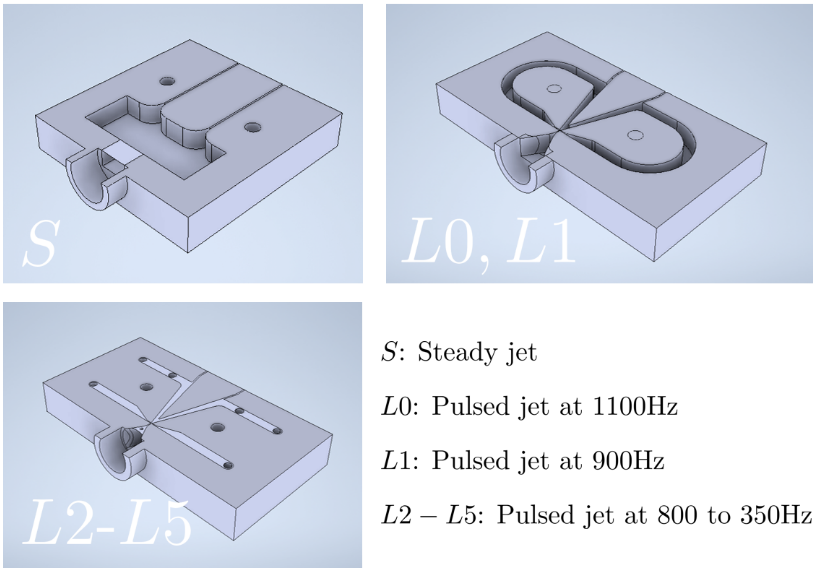

Figure 1: CAD drawings of the prototypes used.

fluidics in terms of speed and size and so the study and development of fluidic devices slowed down for several decades before they were eventually re-purposed for applications such as active flow control or heat transfer.

In the present work, a fluidic Pulsed Jet Actuator (PJA) is used to cool a heated surface. The prototype used produces a pair of pulsating jets that are 700µm wide. The experiments were performed at jet Reynolds numbers of 2000 to 5000 and pulsation frequencies of 177Hz to 1240Hz. The Nusselt number across the surface is computed from temperature measurements and used to evaluate the performance of the device. We also study the frequency response of the PJA's to different design and operating parameters such as the length and width of the feedback loops and the supply pressure. Changing the frequency was shown to affect the intensity of heat transfer in different ways depending on the standoff distance H between the jet slots and the plate.

2 MATERIALS AND METHODS

We begin by characterizing the response of the fluidic actuator to different operating and design parameters. For relatively long feedback loops, Wang et al. have shown that jet switching inside the oscillator depends on pressure waves that move back and forth across the feedback channels. They were able to relate the frequency of the device directly to the length of the feedback channels by neglecting the time it takes the jet to switch from one branch to the other. Loeffler et al. [1] studied devices with a design similar to that of Wang et al. [2] but with a secondary attachment wall in the switching zone. For certain design parameters, they found that changing the mass flow rate of the device could alter the switching mechanism of the jet leading to different pulsation regimes. In other words, sudden changes in frequency can occur between different ranges of mass flow rate. In the present work, we use the design found in [2] but with a wider range of feedback loop lengths and different feedback loop widths. Pressure variations inside the feedback loops are measured and used to compute the frequency of the device. The different models are shown in Figure 1

For the thermal measurements, an ITO-coated glass plate is used as the heated target surface and the temperature field on the uncoated side of the plate is measured using an infrared camera. Samples of the

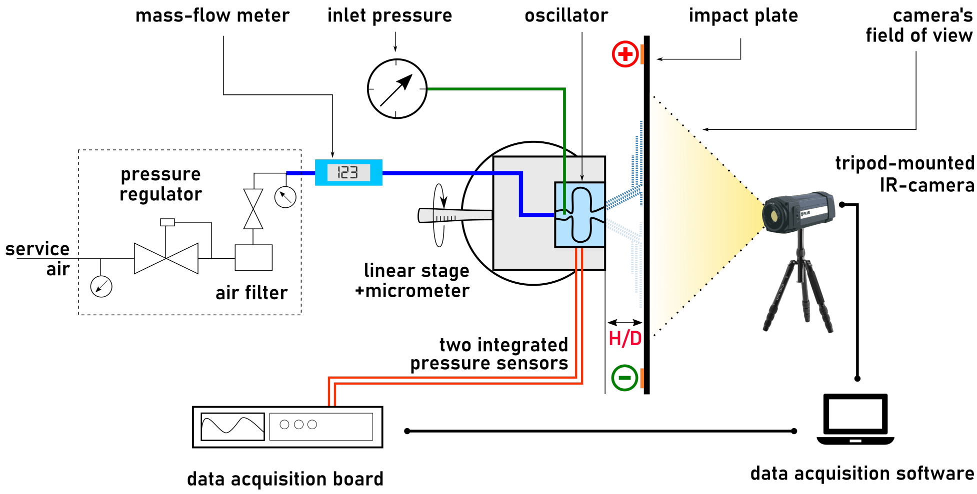

Figure 2: Experimental setup for the measurement of the temperature field on the impact plate.

glass were tested first. The samples are heated inside a spectrometer and the emitted flux $\phi_{\text{sample}}(\lambda, T)$ is measured at different temperatures. The emissivity is then computed relative to a reference (a bar painted in black that is inside the spectrometer). The resulting spectrum is then integrated in the spectral range $[\lambda_1, \lambda_2]$ of the IR camera. Since the average emissivity was higher for the glass side (0.8) than the ITO side (0.53), the thermal measurements were performed on the former. The variability of emissivity with temperature was taken into account when processing the data from the infrared camera.

The temperature field $T(x,y)$ is measured for different values of the heat flux density q" on the plate. A linear regression is performed on the data $q" = f(T)$ to obtain $q" = AT - B$. Then, according to Newton's law of cooling:

$$q" = h(T - T_a) \tag{1}$$

the slope A of the linear trend corresponds to the convective heat transfer coefficient h while B represents the products of h by the adiabatic temperature T_a. The experimental setup is presented in Figure 2

3 RESULTS

Prototypes L3-L7 and Ls3-Ls7 have FBL lengths L ranging from $L^* = L/w_{exit}$= 18 to 100 where w is the width of the exit slots, so that L7 and Ls7 have the longest FBL's. The width of the feedback loops is 2.4 times the exit slot width w_{exit} for the L-prototypes and $1.1 w_{exit}$ for the Ls-prototypes. The change of feedback loop width has a drastic effect on the frequency response of the device. In Figure 3a, the frequency of the L-prototypes increases steadily with supply pressure before slowing down at around $p_s = 2\,\text{bar}$. For the L3 and L4 prototypes, the frequency then continues to rise whereas for the remaining cases it levels off for high values of p_s. The Ls-prototypes on the other hand exhibit a more complex response to supply pressure.

Unlike the L-prototypes, the Ls-prototypes (Figure 3b) begin to produce pulsations at $p_s > 1.6\,\text{bar}$ (the no-pulsation region is shaded in grey). Most of the Ls cases then closely match their L counterparts up to a pressure of $p_s = 2.5\,\text{bar}$. The Ls7 and L7 remain identical up to $p_s = 4.2\,\text{bar}$. The remaining Ls-cases go through an unstable phase (red shaded region) where their frequencies switch erratically

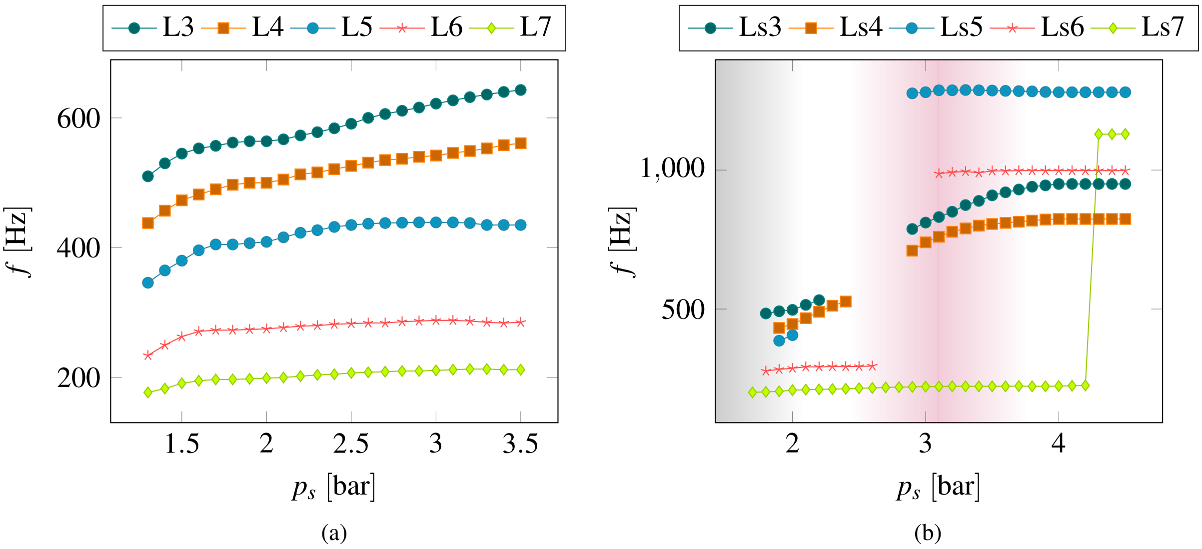

Figure 3: Frequency curves for the (a) L- and (b) Ls-prototypes.

between two values: their last stable frequency before entering the red zone and the one that they will reach after it. Cases Ls3 through Ls6 can then be split into two groups. The first group, Ls6 and Ls5, exit the unstable region with very high frequencies that remain constant with pressure. The second group, Ls4 and Ls3, switches to a frequency that is slightly higher than it was before the transition region. The frequency continues to increase gradually before reaching a plateau at around $p_s = 3.7\,\text{bar}$. Additional cases were also studied, namely L2 ($w^* = 2.4$ and $L^* = 14$), L1 ($w^* = 4.6$ and $L^* = 11$), and L0 ($w^* = 4.6$ and $L^* = 8$), but their results are not included here for the sake of brevity.

These prototypes were then used to perform thermal measurements on a heated glass plate. The maximum Nusselt number for cases L0 and L1 at $Re_w = 6700$ and $H/w = 1$ to 7. For cases L2-L5 (Figure 4), the maximum Nusselt number mainly decreases with standoff distance H/w. For cases L0 and L1, the Nusselt number exhibits a relatively slow decline up to $H/w = 4$. The L0 case outperforms the steady case in the range $H/w = 1-4$ and L1 for $H/w < 3$. The distinct peak in Nusselt number at around $H/w = 4$ for the steady case was observed early on by Gardon and Afkirat [3]. This feature seems to be inhibited by pulsating the jet at relatively low frequencies. In addition, considering that there is only a 25% difference in frequency between L0 and L1, the gap in Nusselt numbers between the two cases implies that heat transfer is sensitive to the pulsation frequency. Overall, improvement in cooling compared to a steady jet can be consistently obtained for small standoff distances, regardless of pulsation frequency.

4 CONCLUSIONS

There is a large number of parameters that intermingle in the study of jet impingement cooling. Although pulsating the jet adds a number of new parameters into play, it offers the experimenter the possibility of adapting the configuration to specific cooling requirements. As we have seen, by changing one parameter, the frequency, it is possible to alter the intensity of heat transfer in response to another parameter, the standoff distance. In addition, fluidic PJA's offer a robust and adaptable alternative to conventional techniques of producing pulsating jets. Nevertheless, there remains a number of questions regarding the influence of certain design parameters on the functioning on these devices, and how they can be leveraged for different applications such as heat transfer.

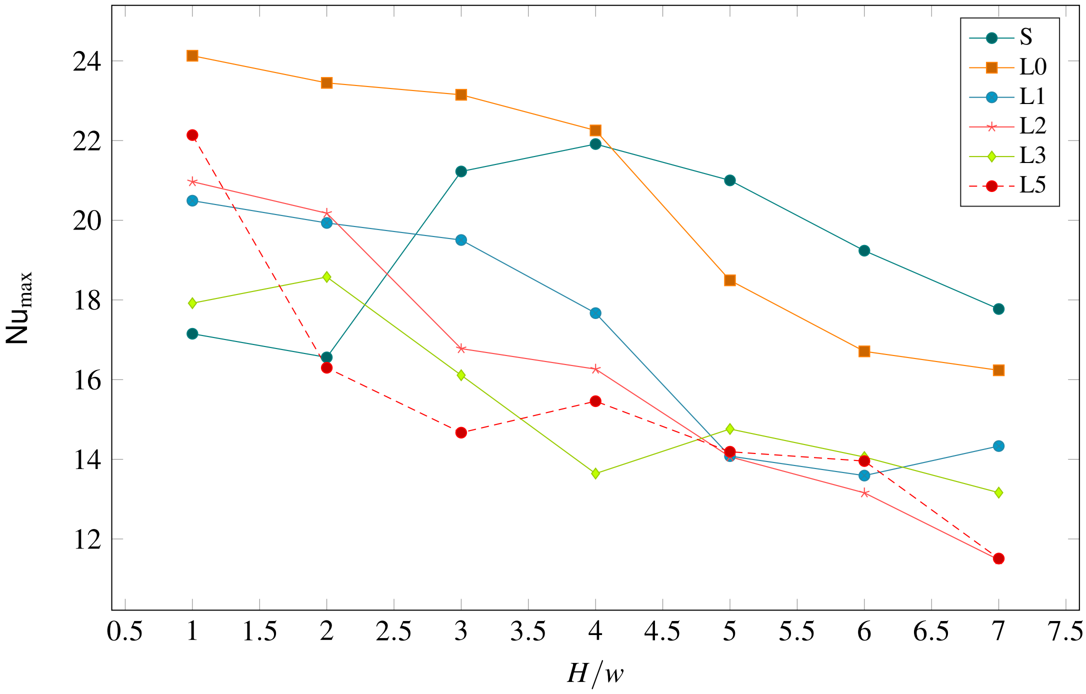

Figure 4: Peak Nusselt number as a function of standoff distance H/w for different jet pulsation frequencies.

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