

Active heat-transfer control by pulsed jet in a turbulent pipe flow at high Reynolds numbers

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Abstract. Control and enhancement of convective heat-transfer in wall-bounded turbulent flows, particularly in pipe flows, is crucial for many industrial applications. A common strategy to enhance heat-transfer is introducing controlled perturbations, such as Jets In Cross-Flow (JICF). Studies have shown that pulsed jets, actuated at specific frequencies and duty cycles, outperform steady jets. However, these findings are limited to a narrow range of Reynolds number, and studies at higher, industrially-relevant values are missing. This work extends the one of Castellanos et al. to higher Reynolds numbers, investigating the scaling of the optimal frequency. Experiments are conducted in a high-Reynolds number facility, namely the Long Pipe at the CICLoPE laboratory. Results show a peak heat-transfer enhancement at 150 Hz, which corresponds to a Strouhal number $St = 6.3$. At 75 % duty cycle and 150 Hz, the pulsed jet outperforms steady-jet actuation, demonstrating enhanced heat-transfer with reduced mass-flow input. Further investigations will assess whether this optimal frequency scales with turbulence parameters as a function of Reynolds number.

1 Theoretical background

Control and enhancement of convective heat-transfer in wall-bounded turbulent flows, particularly in pipe flows, are crucial for many industrial applications [1, 2]. Among different strategies to enhance heat-transfer, introducing controlled perturbations, such as cross-flow jets, generates specific vortical structures that increase Reynolds stresses, enhancing momentum and thermal diffusivity. In particular, jet in cross-flow (JICF) is an active flow-control characterized by four main coherent turbulent structures are identified: shear-layer vortices dominating the initial jet development, a system of horseshoe vortices forming around the jet base, the Counter-rotating Vortex Pair, and wake vortices extending from the wall into the jet[3].

Due to the rapid time scales characteristic of turbulent flows, a steady jet may not be the most efficient way to introduce these perturbations. In fact, pulsed jets actuated at specific frequencies and duty cycles were shown to outperform steady jets. In particular, several studies [4, 5] demonstrated that intermittent pulsating jets cause an increase in convective heat-transfer with respect to steady jets. Furthermore, Eroglu and Breidenthal[6] state that square-wave excitation generates distinct vortex rings which can increase up to 70 % the penetration of the vortical structures: they attributed this improvement to the enhanced vortex dynamics generated by the pulsation. Broadwell and Breidenthal[7] assert that the



velocity ratio, defined as the ratio between jet and main-flow velocity, influences the penetration and bend of the injected flow, as well as the appearance of different flow structures. Castellanos et al. [8] demonstrated that there is an optimal frequency of pulsation, mostly related to a characteristic length-scale of the turbulent flow, that maximizes the heat-transfer coefficient. However, these findings are limited to a narrow Reynolds number range. Therefore, in order to investigate the scaling of the optimal frequency, the work of Castellanos et al. must be extended to higher Reynolds numbers. Due to the large dimension of the facility, the Long Pipe in CICLoPE (0.9 m inner diameter (D) and 111.5 m length [9]), offers the possibility of performing detailed measurements at industrially-relevant Reynolds numbers Re_τ up to 50 000 ($Re_D = 3 \times 10^6$).

2 Experimental setup

The experimental setup employed to investigate wall convective heat-transfer enhancement induced by a pulsed slot jet is shown in Fig. 1:

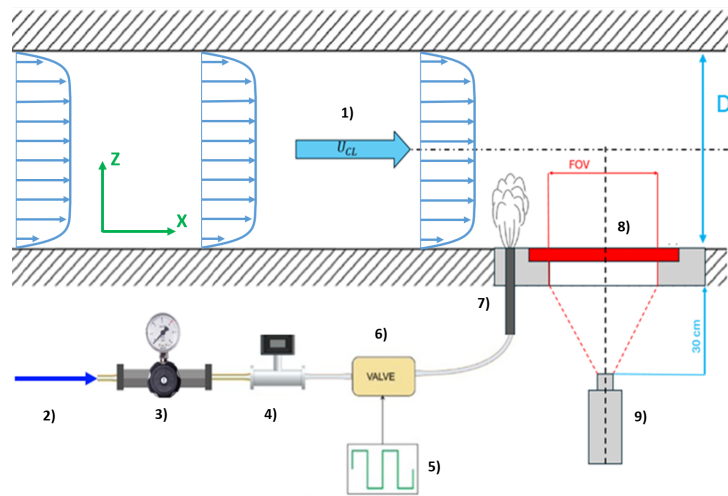


Figure 1: Schematic of the experimental layout: 1) main flow; 2) compressed air; 3) pressure regulator; 4) mass-flow meter; 5) electronic control circuit; 6) solenoid valve; 7) pulsed slot-jet; 8) printed circuit board; 9) infrared camera.

Compressed air is supplied by an external air compressor unit, equipped with a 3-stage drying circuit. The inlet pressure (P_{in}) is regulated by an electronic pressure regulator (REGTRONIC IO-Link NEW DEAL), and set to a constant value equal to 2 ± 0.01 bar (accuracy, from datasheet, is equal to $\pm 0.3 \% \times \text{Full Scale}$). The flow-rate is measured with a mass-flow meter (Honeywell- HAFUHT0200L4AXT), controlled by an Arduino-Uno board (12 bit resolution).

Subsequently, an electronic circuit board creates a square waveform controlled both in frequency and duty cycle, which feeds the solenoid valve: it is composed by a (square) wave generator (C-DAQ 9189 + Module 9263), an adjustable power supply (Elektroautomatik PS2042B) and a mosfet (IRFZ-44N) which acts as a switch. The solenoid valve (SMC SX12F-DH) is the high-speed actuator for the square-wave signal generated by the electronic circuit. It is a normally-closed solenoid valve, designed for a maximum flow rate equal to 50 L/min, a maximum operating pressure equal to 6 bar and a maximum pulsation frequency equal to 350 Hz: indeed, this valve is certified for an opening and closing response time, respectively, equal to 1.25 and 0.4 ms (for $P_{in} = 2.5$ bar).

The solenoid valve leads the air to a slot-jet, flush-mounted to the wall so to eject air perpendicularly to the main (turbulent) pipe-flow generated by the Long Pipe wind tunnel. Downstream the slot-jet, a Printed Circuit Board (PCB) is mounted at the wall and acts as a heat-flux sensor: once supplied with electric power, it heats up and creates a temperature difference with the wall. To assess the convective heat-transfer effectiveness at the wall, the temperature of the PCB is measured with an infrared (IR) camera (FLIR T560) positioned outside the wind tunnel.

2.1 Slot-jet design

The jet, depicted in Figure 2, was designed to ensure the most uniform velocity profile at the exit: as a matter of fact, the design proposed by Castellanos et al. was found to produce a non-uniform velocity profile at the exit of the jet. Therefore, having as fixed design parameter the inlet diameter ($W_1 = 3.96$ mm) and the half of the outlet length ($L = 12.5$ mm), the slot-jet has been designed as follows:

- Diffusion length (N) = 125 mm;
- Diffusion angle (Θ) = 4.8° ;
- Spanwise extension (λ) = 25 mm;
- Streamwise extension (d) = 1 mm;
- Absence of internal guide vanes.

A spanwise investigation (along the y-direction) of the jet exit velocity was performed at the centerline of the jet. The corresponding velocity profiles, for varying input pressure, were obtained on an external test bench, by means of hot-wire anemometry (HWA): each point corresponds to the mean velocity of a signal acquired for 60 s, with a distance of 3 mm from the jet exit, with a sample rate equal to 30 kHz. The results are shown in Fig. 3, where the origin of the reference system $O = f(x, y) = (0, 0)$ corresponds to $d/2$ in the x-direction and to $\lambda/2$ in the y-direction.

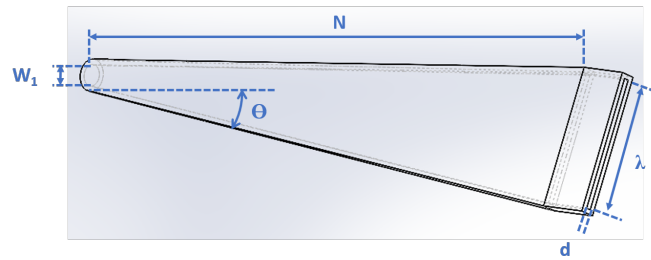


Figure 2: Jet design parameters.

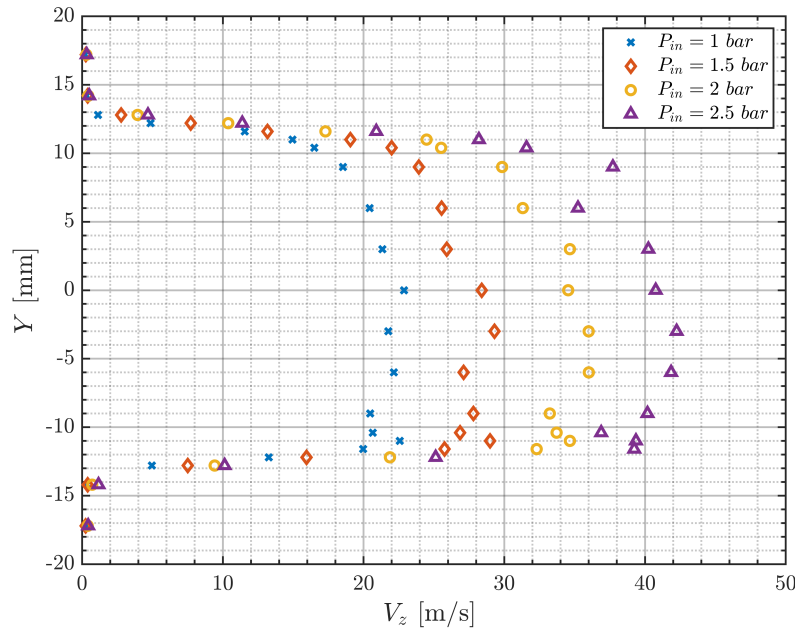


Figure 3: Jet spanwise velocity profiles for different values of input pressure. For the input pressure considered in this work ($P_{in} = 2$ bar) and the lowest Reynolds number reported here ($Re_\tau = 31,450$), the exit velocity corresponds to a velocity ratio equal to 1.

2.2 PCB layout

The test surface is a thermally-thin flexible PCB flush-mounted to the wall of the Long Pipe test section and positioned downstream of the jet. It acts as a heat-flux sensor, consisting of a 55×55 mm² fiberglass board with a thickness (t) equal to 250 μ m, covered by a thin copper-track (track thickness 18 μ m, gap between tracks 0.2 mm, track width 1.8 mm) that provides a quasi spatially-uniform heating when electric current is applied. A very important parameter that must be evaluated when designing a PCB is the Biot number (Bi), defined as:

$$Bi = \frac{h \times t}{k} \quad (1)$$

where h is the convective heat-transfer coefficient, t is the thickness of the PCB and k is the thermal-conductivity coefficient of the foil.

3 Methodology

Once heated, the PCB temperature was measured using the IR camera (frame rate = 30 Hz) and used to compute the convective heat-transfer coefficient h . Indeed, by assuming:

- negligible conductive heat-flux from the surface of the sensor to the support;
- negligible thermal gradients across the thickness of the PCB (since $Bi \ll 1$);
- steady-state condition.

the following energy balance equation can be written:

$$h = \frac{q''_{joule} - q''_{rad} - q''_{cond}}{T_w - T_{aw}} \quad (2)$$

where q''_{joule} , q''_{rad} , and q''_{cond} are the heat fluxes from Joule heating, radiation, and conduction, while T_w and T_{aw} are the PCB and air temperatures, respectively. Radiative heat flux to the environment

is estimated assuming that the environment behaves as a black body at a temperature equal to that of the freestream, while the conductive heat flux is estimated adopting the approach proposed by Torre et al.[10]: a more detailed explanation of the procedure can be found in Castellanos et al[8]. The pulsation frequency is written in a non-dimensional form introducing the Strouhal number (St), while the convective heat-transfer coefficient through the Nusselt number (Nu), defined by Eq.(3):

$$Nu = \frac{h \times D/2}{K_{air}}, \quad St = \frac{f \times D/2}{c} \quad (3)$$

where c is the convection/advection velocity of the large-scale turbulent structures moving within the turbulent boundary layer, equal to $10 \times u_\tau$ and K_{air} is the air thermal conductivity. The value of c was chosen in agreement with literature findings, in particular with the work of Castellanos et al.

A map of Nu values is reported in Fig. 4:

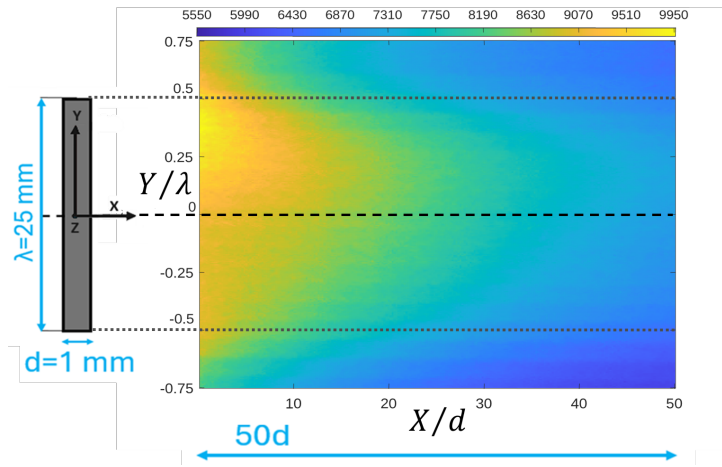


Figure 4: Nusselt number distribution for the steady-jet (SJ) actuation.

The local Nusselt number was spatially averaged by integrating the values over the test surface:

$$\overline{Nu} = \frac{1}{1.2\lambda \times 40d} \int_{-0.6\lambda}^{0.6\lambda} \int_0^{40d} Nu(x,y) dx dy \quad (4)$$

Then, the heat-transfer enhancement is quantified as $\overline{Nu}/\overline{Nu}_0$, where the subscript "0" corresponds to the non-actuated case.

3.1 Experimental parameters

The tests were carried out at constant input pressure ($P_{in} = 2$ bar), with pulsation frequencies between 25 Hz and 300 Hz and duty cycles of 25 %, 50 %, and 75 %. The velocity ratio (R) was changed by varying the centerline velocity, therefore also the Re_τ value. A brief summary of the experimental parameters used during the tests is presented in Table 1:

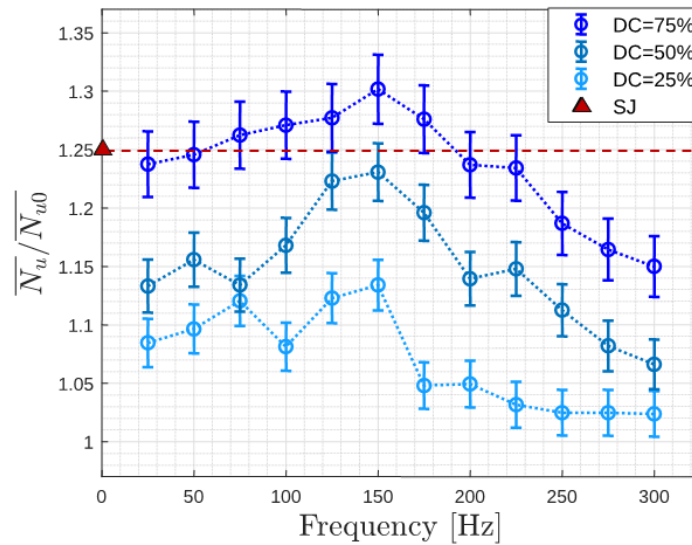
4 Preliminary results and discussion

4.1 Pulsation frequency dependency

To evaluate the effect of frequency on convective heat transfer, the pulsation frequency was varied between 25 Hz and 300 Hz, with steps of 25 Hz, for all values of the duty cycle and $Re_\tau = 31,450$; the result is shown in Fig. 5:

Actuation parameters	Symbol	Value
Jet orientation		Perpendicular to the cross-flow
Jet cross-section	$\lambda \times d$	25×1 [mm]
Jet inlet pressure	P_{in}	2 [bar]
Jet mean velocity	V_{jet}	32 [m/s]
CICLoPE centerline velocity	U_{CL}	32, 37.6, 43.7 [m/s]
Turbulent Reynolds number	Re_τ	31450, 37270, 40240 [–]
Input pulsation frequency	f	From 25 to 300 with steps of 25 [Hz]
Input duty cycle	DC	25, 50, 75 [%]
Velocity ratio	R	1, 0.85, 0.7 [–]

Table 1: Overview of the input parameters of the experimental campaign.

Figure 5: Normalized Nu ($\overline{Nu}$) versus pulsation frequency for different Duty Cycle values[11].

Initially, with the increasing frequency, the heat-transfer increases, reaches a peak and then rapidly decreases; this non-linear behavior is consistent for all duty cycle values. Notably, for a given duty cycle, experimental results suggest the existence of an optimal actuation frequency, which maximizes the Nusselt number, observed at $f = 150$ Hz ($St = 6.3$). The highest absolute performance is achieved with an input duty cycle equal to 75 % at this frequency, resulting in a Nusselt number even higher than that of the steady-jet case, despite the lower amount of air being injected. The presence of the peak of the heat-transfer enhancement at the same pulsation frequency for all DC values, may be indicative of the length and time scales governing the phenomenon. On the other hand, the sharp decline in the Nusselt number at higher frequencies is likely due to the above-mentioned valve delays, which become increasingly significant as the frequency increases, causing the period to decrease.

4.2 Duty cycle influence

The duty cycle has a direct effect on the convective heat-transfer enhancement since it is directly related to the amount of air injected and thus to the momentum added to the system and to the jet penetration. The results, corresponding to $Re_\tau = 31,450$, are shown in Fig. 6:

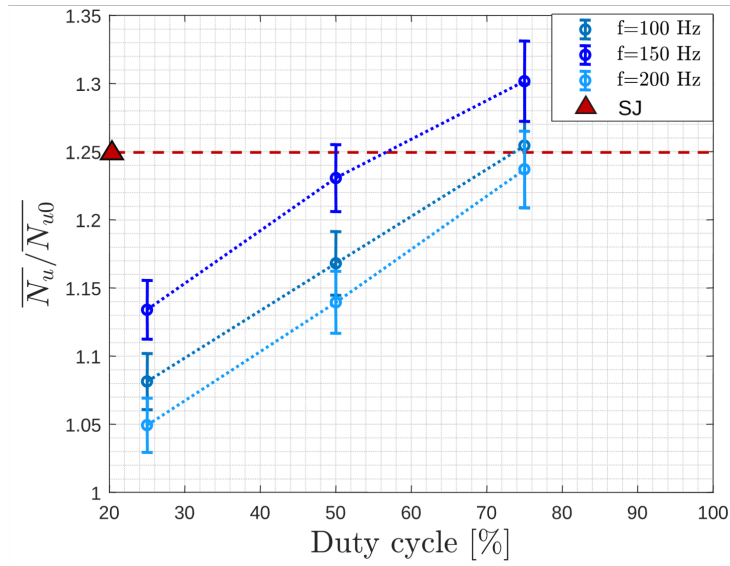


Figure 6: Normalized Nu ($\overline{Nu}$) versus Duty Cycle for different pulsation frequency values.

As expected, a monotonic trend was observed between the Nusselt number and the duty cycle. Nevertheless, a clear separation between the effect of pulsation frequency and duty cycle is not so trivial: as a matter of fact, the opening and closing delay times of the solenoid valve become more and more relevant as the number of cycles increases. This effect exacerbates the reduction in the effective duty cycle and, consequently, the amount of air effectively injected.

4.3 Reynolds number variation

The velocity ratio was modified by changing the main flow velocity, which in turn altered the friction Reynolds number (Re_τ); the results are shown in Fig. 7:

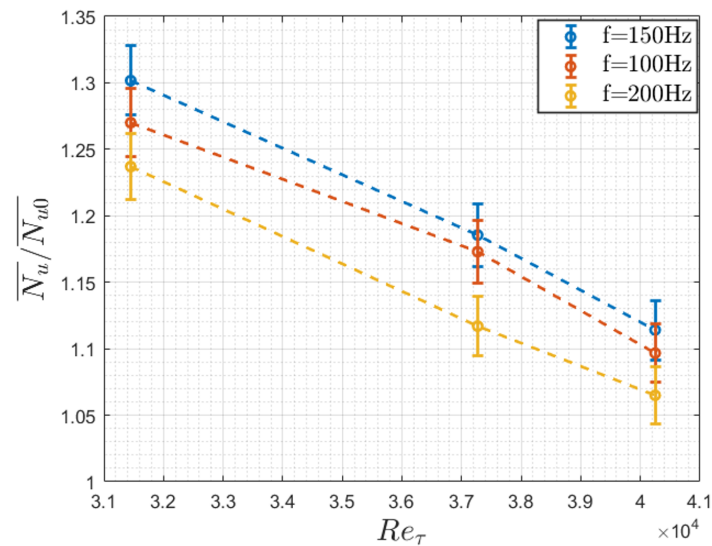


Figure 7: Normalized Nu ($\overline{Nu}$) versus friction Reynolds number for different pulsation frequency values.

As Re_τ increased, a progressive decay of the Nusselt number was observed. Consequently, the convective heat-transfer enhancement induced by the jet became less significant compared to the contribution

of the turbulent flow itself. A possible explanation for this behavior could be reduced jet penetration or a frequency mismatch between jet pulsation frequency and turbulent structures.

5 Conclusions and future work

Pulsed jets in cross-flow were experimentally investigated as a means of controlling heat transfer in a high-Reynolds-number turbulent pipe-flow. The results revealed a monotonic relationship between the average Nusselt number ($\overline{Nu}$) and the duty cycle, whereas the dependence of ($\overline{Nu}$) on the actuation frequency was non-monotonic: the heat-transfer rate increased with frequency up to a peak value, followed by a rapid decline at higher frequencies. Remarkably, in certain conditions pulsed jets achieved enhanced convective heat-transfer compared to the steady jet case, despite involving a lower overall mass of injected air. The physical mechanisms governing this behavior are not yet fully understood and warrant further investigation.

Future work will focus on several improvements to the experimental setup: a higher-performance solenoid valve will be employed, featuring both a higher maximum actuation frequency and shorter delay times for opening and closing. Specifically, the SMC SX12F-BH valve will be used, characterized by opening and closing delay times of 0.55 ms and 0.4 ms respectively, and a maximum pulsation frequency of 1000 Hz.

Furthermore, a temperature sensor (NTC thermistor) will be installed downstream of the solenoid valve to provide more accurate thermal monitoring. Indeed, the energization of the solenoid valve may increase the temperature of the air injected into the flow. Although this effect is expected to be negligible and was not considered in previous studies, it warrants further investigation.

Moreover, the installation of a Germanium window will allow direct optical measurements to be performed. Finally, the application of Temperature-Sensitive Paints (TSP) is expected to enable correlation between surface-temperature data acquired by the infrared camera and those obtained from a conventional high-speed camera.

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