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# Effect of Pulsating Circular Hot Air Jet Frequencies on Local and Average Nusselt Number

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**Abstract:** The study was carried out to determine the effect of pulsating frequencies on the local and average heat transfer characteristic of a heated circular air jet. The velocity profile of a heated circular pulsating air jet was measured in the first part of the study. The same set-up was used to measure the heat flux of the pulsating jet impinging on a wall. The heat flux of the heated air jet impinging on the plate was measured using a heat flux microsensor at different radial positions. Measurement of the heat flux was used to calculate the average and local Nusselt Number for different pulsating frequencies and at different flow Reynolds Number. The pulsating frequencies were between 10-80 Hz and the Reynolds number used were 16 000, 23 300 and 32 000. Results obtained show that the local Nusselt number calculated were higher at all radial position away from the stagnation point. The pulsed jet Nusselt number was higher than the average steady jet Nusselt number for all values of frequencies due to the higher localised heat transfer. The higher Nusselt number obtained at localized radial positions can be due to the higher instantaneous velocity as was shown from the velocity profile plotted in the first part of the experiment. Enhanced turbulence intensity found was due to the pulsed jet.

**Key words:** Pulsating air jet, jet frequency, Nusselt number, heat transfer coefficient

## INTRODUCTION

Jet impingement has been used in many applications of heat transfer such as the cooling of electronic equipment, aircraft engine nacelle and blade, drying of textiles, annealing of metals and tempering of glass. Study on the effect of pulsating frequencies on the impingement heat transfer has been a focused of many researches in the past[1-4]. If enhanced heat transfer can be obtained by pulsing an air jet, a lot of savings can be made from efficient heating or cooling system which can lead to reduced costs. Earlier findings regarding the effect of pulsation on heat transfer have been conflicting due to many different factors. Pulsating a flow is widely believed to increase the heat transfer rate but in some cases the literature shows that heat transfer decreases.

Test carried out by Nevins and Ball[5] on heat transfer between a flat plate and a pulsating jet showed that no significant heat transfer enhancement was obtained by using a pulsed air jet. The test was conducted at $1200<Re<120\ 000$, $10^{-4}<St<10^{-2}$ and non-dimensional nozzle to plate spacing of 8-32. Nevins and Ball[5] did not document the extent of secondary flow structures in their experiments and since the experiment was studied at a very low Strouhal number this might affect their ability to demonstrate pulsed flow heat transfer enhancement. The application of pulse air jet was left dormant for many years due to this earlier finding and the difficulty of accurately controlling many pulse air jet parameters.

Recently, more researchers started to study experimentally and numerically the effect of flow pulsations on heat transfer enhancement. Sheriff and Zumbrunnen[6] investigated experimentally the effect of flow pulsation on cooling performance using arrays of jet. The present of coherent structures was reported but no significant enhancement with respect to the heat transfer characteristics was recorded.

Azevedo *et al*.[7] investigated impingement heat transfer using a rotating cylinder valve for a range of pulse frequencies. The results show that heat transfer

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degraded for all frequencies. In their experiments, velocity profile of the pulse jet shows the existence of a two-peak region for every flow cycle which lead to lower pulse magnitude. The pulse flow profiles have an effect on the heat transfer distribution and could explain why the rate of heat transfer is decreasing at higher pulse frequencies. The dependence of pulse characteristics on convective heat transfer was discussed by Mladin and Zumbrunnen[6].

In pulsed flows, the size and formation of coherent structures are influenced by the amplitude and frequency[6,8]. Large coherent flow structures can evolve from shear layers formed between a free jet flow and a surrounding fluid. The formation and interaction of flow structures can be influenced by the mixing within the boundary layer and a marked increase in turbulence intensities has been noted with pulse flows. Recent findings on the enhancement of heat transfer due to pulse air jets have encouraged new research in this subject. Comprehensive data showing the effect of pulse frequency on local and average heat transfer profile are still limited and there is need of further investigation.

The purpose of this study is to investigate steady and pulsating single circular jet heat transfer characteristics. The focus of the study is given on the effect of flow pulsation frequencies on the average and stagnation Nusselt number. The study is also trying to find out the possibility of controlling the flow structure in pulsating air jet which leads to enhancement in the heat transfer characteristics. Comparisons between steady and pulsed jet heat transfer was discussed in details together with other published results. In this paper the stagnation point Nusselt number of a pulse jet means the time average value at the impingement point of the jet axis. The local Nusselt number of a pulse jet is the time average at a point on the impingement surface. The local Nusselt number is assumed to be radially symmetrical about the stagnation point. The average Nusselt number of a pulse jet is both a time average and an area average over the impingement surface. The total heat flux is proportional to the average Nusselt number.

## MATERIALS AND METHODS

**Pulse flow system:** Figure 1 shows the schematic diagram of the experimental test set-up. The pressurised air used in the experiment is supplied through the compressor. The air is continuously fed through a permanent piping to the heating chamber and the nozzle. The supply pipe of the air storage compressor tank is controlled by a stop valve. A pressure regulator

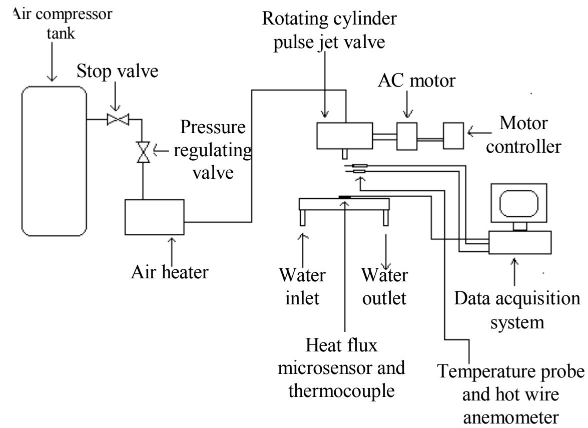


Fig. 1: Schematic diagram of the experimental test set-up

was placed in between the air heater and the stop valve to regulate the supply of air. A vortex flow meter is placed just downstream of the pressure regulator and is used to measure the mass flow of the air jet impinging on the surface of the plate. An air heater is used to heat the air jet with an associated maximum air temperature of 60°C.

The pulse air jet is generated using a rotating cylinder valve driven by an electric motor controlled by an electronic motor controller. The system consists of a rotating cylinder enclosed inside a block aluminium alloy body. A 20 mm diameter hole was bored in the rotating cylinder normal to its axis to allow air passage. The aluminium alloy body is fixed to the supporting shaft and has a 40.2 mm hole diameter bored through its centre. The cylindrical rotating has a diameter of 40 mm and it was aligned inside the body such that a 0.1mm radial clearance is achieved between the stationary body and the cylindrical valve. This led to minimal leakage through the gap with the valve is in the closed position.

The 15 mm diameter shafts at each end of the rotating valve were press-fits on sealed bearings to prevent air leakage through the shafts when the valve is closed. A 20 mm diameter hole was bored on each side of the aluminium block and the hole was aligned with the hole through the rotating cylinder. One end of the bored hole was connected to the compressed storage air tank and the other end was connected to the jet nozzle. In the tests, a jet nozzle of 20 mm diameter and length of 50 mm was used.

**Heat transfer measurement:** Heat transfer measurements were recorded from a heat flux microsensor bonded on the water-cooled aluminium block. The impingement block was constructed from two 12 mm thick, 300 mm by 300 mm wide aluminium plates. Both plates were milled to a depth of 10mm so that only a 2 mm thick wall between the impingement area and the water passage remained. The plates were bonded to each other to create a water-tight aluminium block. Three 12 mm connecting nozzles were attached to the lower part on the rear of the block to allow the cooling water in and another three on the upper part to allow the discharge of the water. Two K-type thermocouples were attached on the rear of the plate at a distance 120 mm apart to monitor the plate temperature. The plate was maintained at a temperature of 20°C throughout each of the tests.

The heat flux of the heated air jet impinging on the plate was measured using a heat flow and integral thermocouple sensor from RdF Corporation. Calibration information and related measurement uncertainties for the sensor was provided by the manufacturer. The sensor is bonded on the plate by a laminating adhesive and is located at the centre of the plate. The impingement plate surface was covered by a Kapton sheet having the same thermal conductivity as the heat flux sensor so that the presence of the sensor would not alter the temperature distribution. The sensor provided voltage outputs corresponding to heat flux and plate temperature.

The values of heat flux and plate temperature for the stagnation point and local measurements at different radial positions were monitored and recorded by the data acquisition system. Local heat transfer measurements were recorded at radial distances from 1-6 nozzle diameters. The instantaneous Nusselt number was calculated using Eq. 2[9]:

$$\mathrm{Nu} = \frac{q''}{(T_j - T_w)} \frac{D}{k} \qquad (2)$$

where q″ is the stagnation point heat flux measured by the sensor, D is the nozzle diameter, k is the thermal conductivity of the air jet evaluated at film temperature, $T_j$ is the temperature of the hot air jet and $T_w$ is the temperature of the plate at the stagnation point. The average Nusselt number based on the local temperature difference was calculated by numerically integrating the heat flux measurement over the impingement area.

## RESULTS AND DISCUSSION

Table 1 shows the values of the parameters that were investigated. The values of both the local and average Nusselt numbers are considered to be functions of Reynolds number and radial distance from the stagnation point. Duty cycle and x/D were not varied in this experiment.

Table 1: Parameters investigated in the experiments

| Parameter | Values |
|---|---|
| Re | 16000, 23000, 32000 |
| St | 0.008<St<0.123 |
| x/D | 4 |
| DC | 33% |
| D | 20 mm |
| F | 10-80Hz |

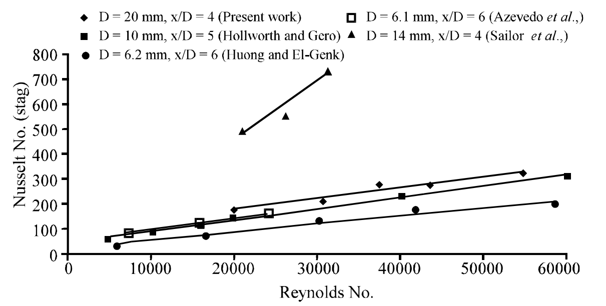


Fig. 2: Comparison of steady flow stagnation point nusselt number

To confirm the accuracy of the present work, the value of the steady jet Nusselt number versus Reynolds number was plotted and compared to the results of several previous researchers work as reported by Jambunathan *et al*.[10]. Figure 2 shows that the measured Nusselt numbers for the steady jet are comparable with previous experiments.

The steady Nusselt number values obtained by Sailor *et al*.[4] were higher than those documented by other research work. Their calculations of Nusselt numbers were based on the difference of temperature between the stagnation point and the local adiabatic wall temperature. The average air temperature at the stagnation point is lower than the air temperature at the jet nozzle because ambient cool air is entrained in the pulse jet. This explains why Sailor *et al*.[4] recorded a higher value of Nusselt number for the same test parameters.

Figure 3 shows the variation of stagnation point and average Nusselt number with Reynolds number at nozzle to plate spacing, x/D equal to 4 for frequencies from 20-80 Hz. Stagnation Nusselt number increases with higher Reynolds numbers as predicted.

Figure 4 shows a graph of local Nusselt number against radial distance for frequencies of 10Hz and 20Hz for all the three Reynolds number under investigation. The graph shows that the local Nusselt numbers for pulse flow is higher than for steady flow at position from 1 diameter outwards. Higher turbulence intensity at these positions is believed to contribute to the increase in heat transfer. The higher turbulence obtained could be due to the higher localized instantaneous velocity as recorded earlier.

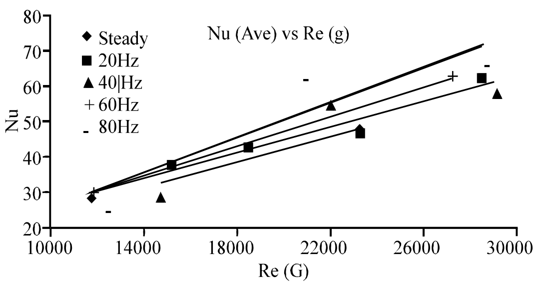


Fig. 3: Variation of stagnation point and average nusselt number with reynolds number, Re(G) at nozzle to plate spacing, x/D = 4 for frequencies from 20-80 Hz

Figure 5 shows a graph of stagnation and average Nusselt numbers against frequency for Reynolds number at 16000, 23300 and 32000. The flow structure changes with frequency in a complex manner so the Nusselt number versus frequency curve shows no clear trend. The average Nusselt numbers for the pulse jet are higher than the steady jet for all the frequencies tested by at least 30%.

The present results show that the average heat transfer on the impingement area is enhanced quite significantly even though the stagnation point heat transfer decreases. These increases are shown to be available for a system that uses a single pulse jet impinging on an area with radius up to 6 times the nozzle diameter. The results show that higher mass flow rate can influence the heat transfer measurements.

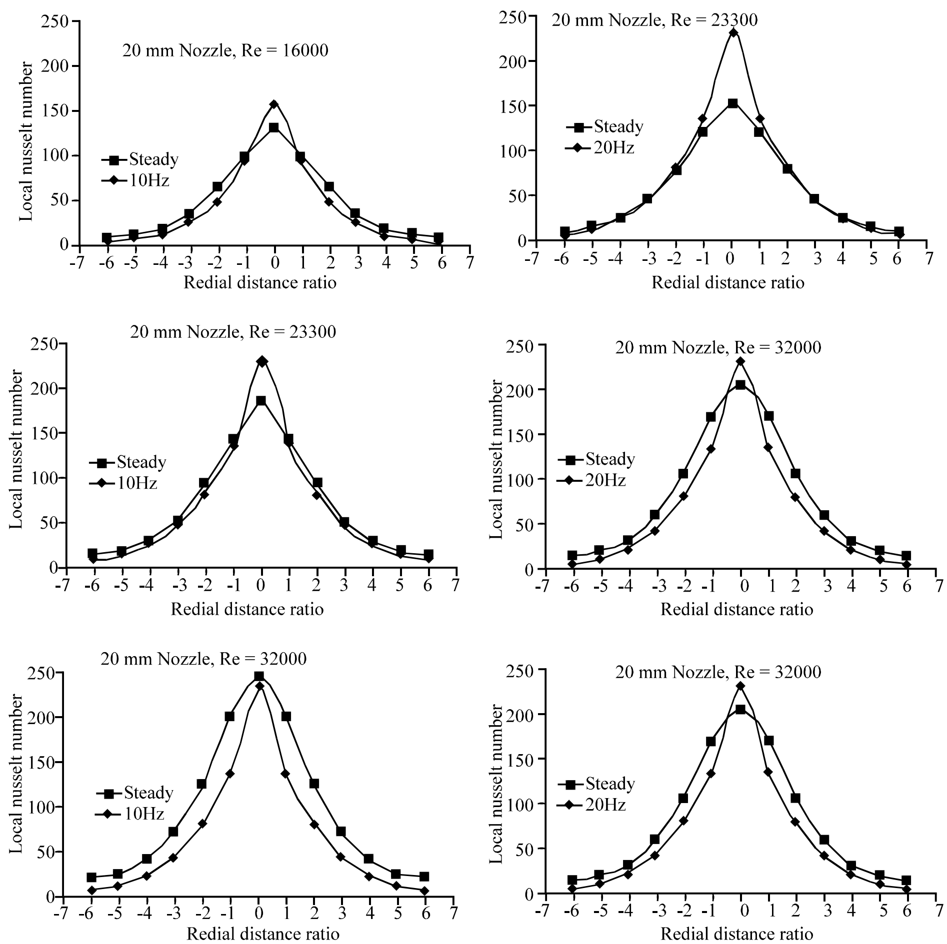


Fig. 4: Variation of local nusselt numbers with radial distance at frequencies of 10 and 20Hz for Re = 16000, 23300 and 32000

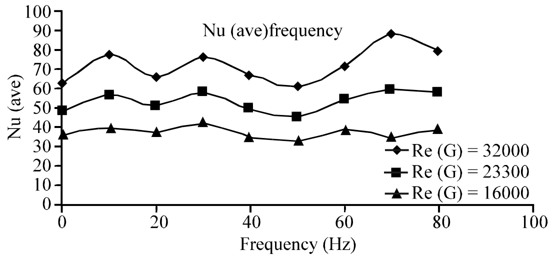


Fig. 5: Variation of stagnation and average nusselt numbers with frequency for reynolds number = 16000, 23300 and 32000

## CONCLUSION

The results of the experiments show that there is significant enhancement in the local heat transfer of the pulse flow at positions one nozzle diameter or more away from the stagnation point for all the pulse frequencies. The stagnation point heat transfer does not show any enhancement for the three Reynolds numbers investigated. The average Nusselt number for the pulse jet is enhanced for all the frequencies investigated. The degree of enhancement is in the range 30-80%. Heat transfer in the pulse flow mode is complex and dependent on the flow structure of the jet. The significant enhancement of the heat transfer at local distances away from the stagnation point resulted in higher average Nusselt numbers for pulse flow compared to steady flow. Significant turbulence intensity caused by pulsating the jet resulted in the increase recorded. The degradation in heat transfer at the stagnation point is believed to be due to small turbulent intensities of the pulse flow at this position.

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