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# THE EFFECT OF AN EXTERNAL EXCITATION ON A HEAT TRANSFER IN AN IMPINGING JET

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## ABSTRACT

Heat transfer in a submerged round water jet impinging on a flat heated plate and the effect of external flow excitation on heat transfer have been experimentally studied using Infrared Thermography. Convective heat transfer in the stagnation point area can be influenced (enhanced or suppressed) by periodic pulsations of flow velocity. In the tested range of flow parameters excitation of the flow at dimensionless frequency *Sh*=0.5 leads to maximum heat transfer reduction. Heat transfer is affected significantly at low nozzle-to-plate spacing. Increased excitation amplitude results in further decrease of heat transfer for *Sh*=0.5.

## NOMENCLATURE

| | | |
|---|---|---|
| $A$ | [%] | Velocity pulsations amplitude, $A = u'/U_0$ |
| $D$ | [m] | Nozzle diameter |
| $f$ | [Hz] | Excitation frequency |
| $h$ | [m] | Nozzle-to-plate spacing |
| $Nu$ | [-] | Nusselt number, $Nu = \varphi D/\lambda$ |
| $q$ | [W/cm$^2$] | Heat flux from the impingement surface |
| $Re$ | [-] | Reynolds number, $U_0 D/\nu$ |
| $Sh$ | [-] | Strouhal number, $fD/U_0$ |
| $T$ | [K] | Temperature |
| $T_{ref}$ | [K] | Ambient temperature |
| $u'$ | [m/s] | Fluctuating axial velocity |
| $U_0$ | [m/s] | Mean axial velocity at the nozzle exit |
| $r$ | [m] | Cartesian axis direction |
| $z$ | [m] | Cartesian axis direction |
| $\varphi$ | [W/m$^2$K] | Local convective heat transfer coefficient |
| $\lambda$ | [W/m K] | Thermal conductivity of water |
| $\nu$ | [m$^2$/s] | Kinematic viscosity |

## INTRODUCTION

Impinging jets due to high heat transfer performance are widely used in industry for cooling, heating or drying. Numerous studies of jet impingement heat transfer have been published. Comprehensive review of that data has been presented by Jambunathan et al [7]. Nusselt number distribution varies in shape and magnitude with various test parameters, namely nozzle-to-plate distance, Reynolds number, nozzle geometry. The near-wall area of the jet can be divided into two zones: stagnation point zone and wall jet zone. At relatively low nozzle-to-plate spacing two local maxima in *Nu* distribution exist in stagnation point zone. The location of secondary maximum coincides approximately with the point where toroidal vortices formed in the shear region penetrate into the vicinity of heated plate; at that location turbulization of boundary-layer flow occurs. Donovan and Murray [4] have performed spectral analysis of heat transfer fluctuations and have shown similarity between axial velocity spectrum and heat flux spectrum in that area.

Various experimental studies of the effect of periodic pulsations of flow velocity on heat transfer were published. Sheriff and Zumbrunnen [10] studied influence of low-frequency ($St$<0.1) pulsations of different amplitude on cooling effectiveness of planar impinging water jet ($h/D$>3). Decrease of heat transfer with increasing pulsations amplitude (40 %<$A$<85 %) at that frequency was addressed to the nonlinear dynamic responses of the hydrodynamic and thermal boundary layers. Liu and Sullivan [8] have shown that at small nozzle-to-plate spacing ($h/D$<2) low-amplitude ($A$<0.18 %) external excitation of the circular air jet flow results in heat transfer enhancement or reduction in the area of secondary maximum, depending on excitation frequency. When excitation frequency is close to the natural frequency of the impinging jet the intermittent vortex pairing was observed which resulted in a break-down of naturally occurring vortices and heat transfer enhancement. Excitation on subharmonics of natural frequency resulted in stable vortex pairing and heat transfer reduction. Donovan and Murray [5] studied impinging jet excited at different frequencies and amplitudes and observed that low excitation amplitude results in heat transfer reduction for all excitation frequencies tested. Hofmann et al [6] studied effect of high-amplitude pulsations on heat transfer. Nozzle-to-plate spacing and pulsation amplitude were shown to determine effect of external excitation on heat transfer at different frequencies leading to heat transfer reduction or enhancement.

Summing up, various mechanisms of heat transfer controlling by external excitation of the jet flow were reported but that data is difficult to be generalized. Periodical excitation of the jet is known to affect primarily the dynamics of large-scale vortices but also mean parameters of the flow (see Crow and Champagne [2], Vlasov and Ginevskiy [11], Zaman and Hussain [12]). The aim of this work is to experimentally investigate heat transfer in the submerged circular impinging water jet with the presence of large-scale vortical structures and flow separations and to study possible mechanisms of heat transfer control by means of external excitation of the flow.

## EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUE

The flow arrangement and coordinate system are schematically shown in Figure 1, experimental setup is sketched in Figure 2. Distilled water circulated in a closed hydrodynamic circuit. Water was supplied by a pump to a circular convergent nozzle with a diameter of $D$=15 mm which generated low turbulence water jet with top-hat velocity profile issuing in upward direction in a water-filled rectangular plexiglass reservoir (0.25 $m^3$). Jet velocity was controlled with orifice plate flowmeter. The jet impinged normally on a flat horizontal surface. Impingement surface (heater) was made of stainless steel foil with thickness of 0.125 mm and was heated using constant current power supply to keep heat flux constant ($q$=1.1 W/cm$^2$). Temperature of water was kept constant with uncertainty of 0.1° C using thermostat. Electro-mechanical oscillator was used to add periodical perturbations of defined frequency and amplitude to the inlet flow velocity. Frequency and amplitude were varied with the aid of computer-controlled DAC converter and voltage divider respectively.

Temperature of the impingement surface was measured with infrared camera (FLIR Titanium 550M, $320\times260$ pixels), which was mounted above the heater and measured its temperature from the backward. For every test case 10000 instant temperature fields were captured to calculate time-averaged radial Nusselt number distribution. Also ambient temperature field $T_{ref}$ (with power supply switched off) was obtained. Nusselt number was defined as follows:

$$\varphi(r)=\frac{q}{T(r)-T_{ref}(r)}$$

$$Nu(r)=\frac{\varphi(r)D}{\lambda}$$

To control perturbations amplitude velocity and velocity fluctuation fields at the nozzle exit were measured by means of Particle Image Velocimetry technique. The flow was seeded with polyamide particles with mean diameter of 20 µm. A light sheet was formed from the beam of pulsed double-cavity Nd:YAG laser (wavelength 532 nm, pulse energy 50 mJ), light scattered by particles was captured by double-exposure CCD camera ($2048\times2048$ pixels). Velocities were calculated with PIVIT ActualFlow software using iterative cross-correlation algorithm with interrogation areas shifting and deformation (described elsewhere, see Raffel et al [9], Alekseenko et al [1]). Amplitude of inlet velocity fluctuations was measured at the jet centerline at the nozzle exit. Turbulence level at that point in an unexcited state was 3 % for $Re$=4000 and $Re$=10000.

External excitation was characterized with Strouhal number (dimensionless frequency) $Sh=fD/U_0$ and velocity perturbations amplitude $A=u'/U_0$ .

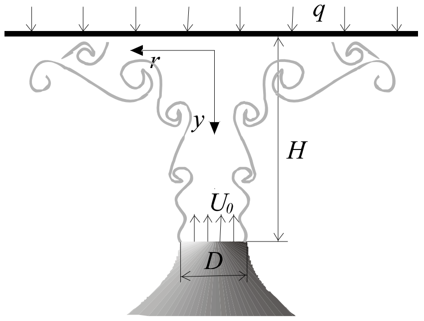

**Figure 1** Flow arrangement and coordinate system

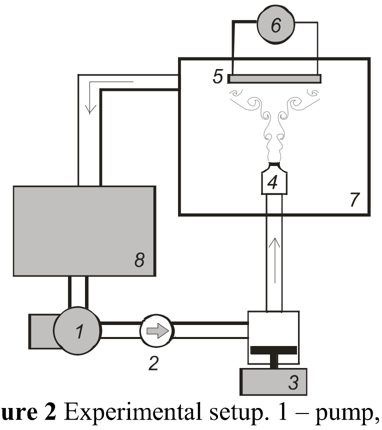

**Figure 2** Experimental setup. 1 – pump, 2 – flowmeter, 3 – oscillator, 4 – nozzle, 5 – heated plate (impingement surface), 6 – power supply, 7 – reservoir, 8 - thermostat

## RESULTS AND DISCUSSION

### Effect of Reynolds number and nozzle-to-plate spacing

Figure 3 and 4 show Nusselt number distributions at natural conditions (*Sh*=0) for different values of Reynolds number and nozzle-to-plate spacing. It is obvious that increase of Reynolds number results in increase of heat transfer. For all cases a local weakly pronounced minimum of heat transfer at the stagnation point (*r/D*=0) is observed which is due to the existence of potential core of the jet at those distances. For *h/D*=1 secondary maximum located at 1.5<*r/D*<2 is more intensive than for *h/D*=3. For higher Reynolds numbers (*Re*>7700) at *h/D*=1 heat transfer is most intensive in the area of secondary maximum.

Figure 5 shows Nusselt number distributions for *Re*=10000 and *h/D* varied from 1 to 7. While heat transfer intensity at the stagnation point changes slightly with *h/D* increasing, secondary maximum value at *h/D*=7 is twice lower than its value at *h/D*=1. Donovan and Murray [4] associated the intensity of secondary maximum with intensity of large-scale vortices which, due to interaction with the wall, break down into smaller scale turbulence enhancing heat transfer. Alekseenko et al [1] have demonstrated that in the wall jet area (*r/D*>2) coherent part of velocity fluctuations, which corresponds to large-scale vortices, decreased while random part increased. Those vortices become less intensive and larger in scale while moving from the nozzle exit due to merging and break-up processes (see Zaman and Hussain [12]). It results in lower intensity of secondary maximum in heat transfer distributions.

In the wall jet area (*r/D*>3.5) *Nu* is not dependent on nozzle-to-plate spacing, as shown in Figure 5.

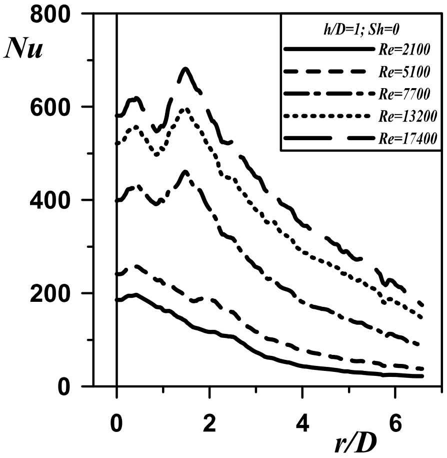

**Figure 3** Influence of *Re* on radial *Nu* distributions (*h/D*=1). Unexcited jet

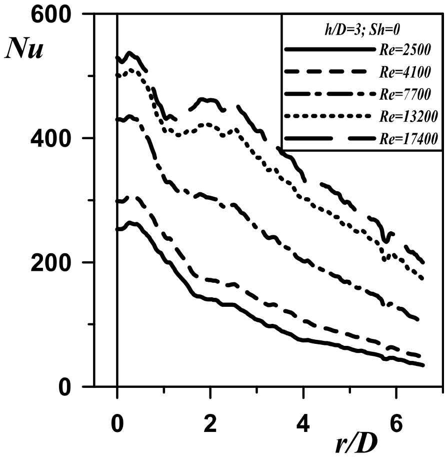

**Figure 4** Influence of *Re* on radial *Nu* distributions (*h/D*=3). Unexcited jet

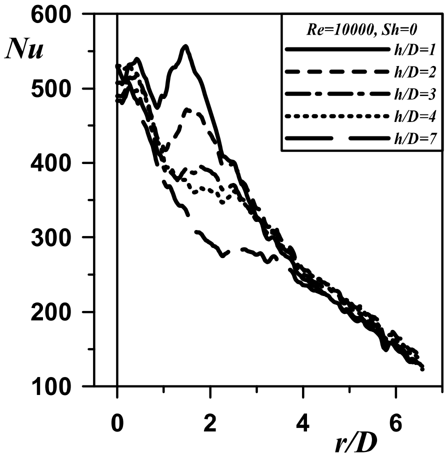

**Figure 5** Influence of *h/D* on *Nu* distribution, *Re*=10000. Unexcited jet

Basic dependencies described above are in good agreement with data reported in literature (see Jambunathan et al [7], Donovan and Murray [3, 4]).

### Effect of excitation frequency

Measurements of heat transfer were performed for several excitation frequencies and amplitudes at *Re*=4000 and *Re*=10000. The tested range of dimensionless excitation frequency was *Sh*=0.4–2.0. Amplitude of axial velocity perturbations at the nozzle exit was varied in the range from 4 % to 20 %. Measured level of natural turbulent fluctuations at the nozzle exit (without external excitation) was 3 % for both Reynolds numbers studied.

Nusselt number distributions for the most representative frequencies and low Reynolds number (*Re*=4000, *A*=8.5 %) are shown in Figure 6. When nozzle-to-plate spacing is low (*h/D*=1, Figure 6) excitation of the flow at frequency corresponding to *Sh*=0.5 results in maximum heat transfer reduction. Excitation on *Sh*=0.9 at that flow conditions lead to slight heat transfer enhancement. Difference in *Nu* averaged over stagnation point area (0<*r/D*<3.5) for the cases *Sh*=0.5 and *Sh*=0.9 is 8 %. For larger nozzle-to-plate spacing (*h/D*=3, Figure 7) heat transfer is less affected by external excitation as shown on Figure 7. For *Re*=10000 heat transfer is more sensitive to external excitation at the same dimensionless frequency and amplitude (see Figure 8).

According to Crow and Champagne [2] and Vlasov and Ginevskiy [11], excitation of the jet flow at frequency corresponding to *St*=0.2–0.6 results in large-scale vortices enhancement, intensification of mixing and shortening of potential core. With higher pulsations amplitude the effect is enhanced. So suppressed heat transfer for *Sh*=0.5 can be addressed to the decreased turbulence level due to high stability and coherence of vortices generated by pulsations of corresponding frequency and also to the decrease of mean flow velocity due to enhanced mixing between jet and environment. When frequency of pulsations is higher (*St*>1.0), generated vortices have smaller scale and break down rapidly due to interaction with other vortices. At higher nozzle-to-plate distances large scale vortices are weaker as mentioned above, so the effect of flow excitation is reduced. Heat transfer in the wall-jet region is less affected by flow pulsations.

Excitation affects heat transfer in a whole stagnation point area (0<*r/D*<3.5). It differs from effect of small-amplitude excitation which affects secondary maximum only [8] but also demonstrates enhancement and reduction of heat transfer depending on excitation frequency. Hofmann et al [6] have presented data for high-amplitude excitation (*A*>15 %) of a jet flow with *Re*>34000. For *h/D*=2 no heat transfer reduction was observed; heat transfer enhancement occurred for frequencies *Sh*>0.2. But that data can't be compared directly with distributions presented here because of different nozzle geometry and significantly lower Reynolds number studied in the present work.

**Effect of excitation amplitude**

Effect of excitation amplitude was studied for *h/D*=1, *Sh*=0.5 and *Re*=10000. Amplitude of axial velocity perturbations at the nozzle exit was varied in the range from 4.5 % to 17 %. Level of natural turbulent fluctuations at the nozzle exit (without external excitation) was 3 %.

Heat transfer coefficient distributions are shown in Figure 8. *A*=3 % is a case without external excitation and actually corresponds to the RMS level of natural turbulent fluctuations (3 %). Excitation affects heat transfer even if perturbations amplitude is comparable with natural velocity fluctuations. Heat transfer decreases in the area of stagnation point (0<*r/D*<2) with increasing amplitude. Secondary maximum in Nusselt number distribution (*r/D* is about 1.5) is mostly affected; heat transfer at that area was decreased up to 35 %.

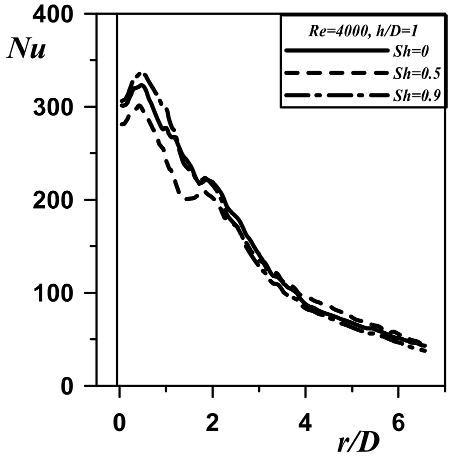

**Figure 6** Influence of excitation frequency on *Nu* distribution, *Re*=4000, *A*=8.5 %, *h/D*=1

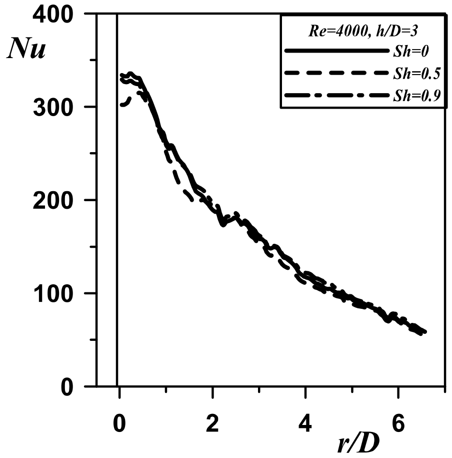

**Figure 7** Influence of excitation frequency on *Nu* distribution, *Re*=4000, *A*=10 %, *h/D*=3

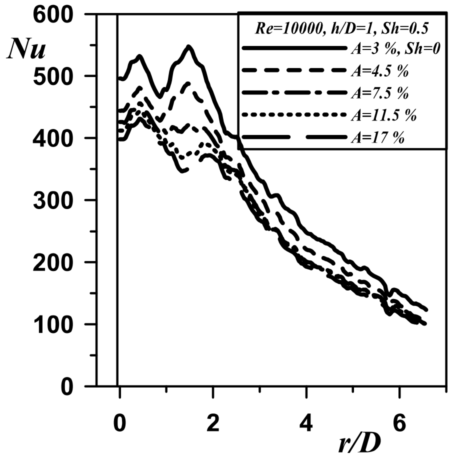

**Figure 8** Influence of excitation amplitude on *Nu* distribution, *Re*=10000, *Sh*=0.5, *h/D*=1. *A*=3 % s a case without excitation (*Sh*=0)

## CONCLUSION

During the experimental study of axisymmetric jet impinging onto heated plate, it was shown that convective heat transfer in the stagnation point area can be influenced by external flow excitation with relatively high amplitude of periodical imposed oscillations. Excitation of the flow on dimensionless frequency *Sh*=0.5 leads to maximum heat transfer reduction in the tested flow parameters range. Heat transfer was affected significantly at low nozzle-to-plate spacing (*h/D*<3). Increasing excitation amplitude results in further decrease of heat transfer for *Sh*=0.5.

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