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Influence of a pulsation on heat transfer and flow structure in submerged impinging jets

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Abstract

An experimental investigation on pulsating impinging jets has been performed. The effect of the pulsation on the flow structure and heat transfer have been investigated. Frequency and amplitude were varied separately and the effect of each parameter was examined for different Reynolds numbers and nozzle-to-plate distances.

The jet was found to become broader and the core jet length smaller with the pulsation. The reason for this behavior is that pulsation enhanced entrainment of air into the jet, which results in a change of mean velocity of the jet. Nevertheless, the behavior at lower frequencies (up to 140 Hz) is still quasisteady. This means that the amplitude of the pulsation behaves similar to the mean velocity of the jet, that the shapes of the velocity profiles are comparable to steady jets and that the jet behavior is independent of frequency.

At moderate frequencies heat transfer is only affected by the pulsation when nozzle-to-plate distance and amplitude are large enough. At small nozzle-to-plate distances enhanced entrainment has no influence and no difference between steady and pulsating jets can be recognized. At large nozzle-to-plate distances entrainment increases and jet velocity reduces. This yields a reduction of heat transfer in the stagnation point of up to 50%.

But besides of this effect of enhanced entrainment a theoretical limit could be determined, above which the jet is not anymore quasisteady. Above $Sr = 0.2$ heat transfer is affected by the pulsation also at small nozzle-to-plate distances. At this frequency boundary layer is also affected by the pulsation. This yields increased heat transfer coefficients at the stagnation point. For larger nozzle-to-plate spacings this effect is superposed by the reduction of heat transfer due to increased entrainment, resulting in a strong decrease of heat transfer coefficient.

Keywords: Jet impingement; Heat transfer; Intermittency; Pulsation; Experiment; Flow structure

1. Introduction

The mechanisms of convective heat transfer in steady single phase flows has been widely examined, but only few knowledge exists about how periodic intermittency affects heat transfer. In many technical applications intermittent flow occurs due to moving parts, like in pumps or turbines or by vibrations or flow oscillations. It is still not clear, which mechanisms take place and how heat transfer is influenced by these phenomena. While for pipe flow only a small influence has been observed [8], for free shear flows no information is available. In order to approach this problem an experimental investigation on the influence of a pulsation on heat transfer and flow structure in impinging jets has been performed. Heat transfer measurements have been carried out by means of thermography and flow measurements have been performed with a laser-doppler-velocimeter. The investigation on the influence of frequency and amplitude on heat transfer at different Reynolds numbers and nozzle-to-plate-spacing has

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Nomenclature

Latin symbols

A	amplitude (m/s)
D	nozzle diameter (m)
f	frequency (Hz)
H	nozzle-to-plate spacing (m)
Nu	Nusselt number ($=\frac{\alpha D}{\lambda}$)
K	number of classes (–)
Pu	pulsation intensity (–)
r	radial distance from stagnation point (m)
Re	Reynolds number ($=\frac{uD}{v}$)
Sr	Strouhal number ($\frac{fD}{u}$)
u	velocity component in axial direction (m/s)
z	axial distance from nozzle (m)

Greek symbols

α	heat transfer coefficient (based on $T_{\text{plate}} - T_{\text{nozzle}}$) (W/(m^2 K))
λ	thermal conductivity (W/(m K))
v	kinematic viscosity (m^2/s)
Φ	phase shift (°)

Subscripts

N	normalized on mean axial jet exit velocity
k	value averaged over particular phase angle range
eff	effective (based on RMS, not on maximum deviation)

Superscripts

$'$	turbulent velocity fluctuation
$-$	mean velocity

resulted in a guideline, how far pulsating jets can be treated like steady jets and which changes occur above this limit.

2. Background

Submerged impinging jets have been examined widely in the second half of the last century. Numerous works on this topic can be found in the literature, which cover the main influence factors on heat transfer and flow structure. Overviews can be found in [1–4]. Newer investigations on steady jets, performed by the authors of the present contribution, can be found in [5]. Already since the forties of the last century the influence of a pulsation on convective heat transfer has been examined. Most of the works deal with a tube flow with a superposed pulsation. A comprehensive illustration can be found in [6,7]. When water as medium is used, cavitation can occur in cases with flow reversal. This causes a drastic increase in heat transfer, but in systems with no flow reversal or in gaseous jets influence of pulsation on heat transfer can be neglected. Fallen [8] has found no influence of pulsation on heat transfer in laminar flow. In turbulent flow he has observed slight increase or decrease, depending on frequency. Fallen has assumed that pulsation influences turbulence intensity and flow in the inlet region, which results in slight changes in heat transfer.

Mladin [9–12] has investigated, how heat transfer in impinging jets is influenced by a pulsation. An analytical model, which describes the response of the boundary layer on changes in the mean flow, predicts a decrease of heat transfer by the pulsation of up to 17% over a large range of frequencies. Only in cases of low amplitude and high frequency a slight increase of 1% in heat transfer has been observed. The results have been validated with experimental data at Reynolds numbers of up to 14,000 and frequencies of up to 70 Hz.

The influence of pulsation on axisymmetrically impinging jets has been examined by Vejrazka [13] at $Re = 10{,}000$ with an amplitude of 1% of the mean flow. He has performed numerous investigations on the temperature distribution in the jet, vortex generation and flow structure, but he has not found any influence of pulsation on heat transfer. Camci and Herr [14] have performed measurements with self-oscillating jet at large distances from the nozzle. The jet became broader, compared to the steady jet. At Reynolds numbers of 7500–14,000 and very large nozzle-to-plate distances ($H/D = 24$–60) strong increases in heat transfer has been observed.

From these investigations it can be concluded that there is still the need for an investigation on the main influence parameters and mechanisms of pulsating flow, especially with large shear layers.

3. Experimental setup

The experimental setup is sketched in Fig. 1. Details about the setup and the procedure are described in detail in [5,15,16]. The experiments were performed with a single round nozzle with a diameter of 25 mm at the exit, where the jet is contracted from a diameter of 50 mm, resulting in a mean velocity of 49 m/s for $Re = 78{,}000$. Nozzle and plate are surrounded by a cylindrical chamber with a diameter of $33 \cdot D_{\text{Nozzle}}$ to ensure, that the experiment is affected by external influences. By initial CFD calculations, it could be shown, that at this size, the flow in observed area is not influenced by the surrounding. The temperature in the far field of the jet was recorded. It was determined to be about