Effect of Signal Combination on Periodic Jet Impingement Heat Transfer (Postprint)

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Date: 2017-11-07T00:00:00+00:00

Abstract

A signal generator was utilized to control a mass flow controller for generating periodically varying unsteady jets with adjustable waveforms and frequencies. This study experimentally investigated the impingement heat transfer performance of periodic waveforms produced by combining standard rectangular, sinusoidal, sawtooth, and step pulse signals, with a frequency range of 1.25 Hz}-20 Hz. The results indicate that the combined-signal unsteady jet influences the average heat transfer coefficient of flat plate heat transfer; the variation of the dimensionless average Nusselt number (Nu) for jet impingement heat transfer at and around the stagnation point primarily depends on the signal variation pattern and frequency; the incorporation of step pulse signals can augment the average Nusselt number of the impinged plate to a certain degree; and combined sinusoidal-rectangular and sawtooth-rectangular unsteady jets can achieve enhanced heat transfer performance compared to steady jets when the frequency exceeds 10 Hz.

Full Text

Influence of Signal Combination on Heat Transfer Characteristics for Periodic Impinging Jet

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Abstract

This experimental study investigates the heat transfer characteristics of periodic air jets generated by combinational signals impinging on a heated surface. The unsteady jets are produced using a signal generator and mass flow controller, enabling adjustable waveforms and frequencies. Experiments are performed for combinations of rectangular, sinusoidal, saw-toothed, and pulsed signals at frequencies ranging from 1.25 Hz to 20 Hz. The results demonstrate that combinational signals significantly influence the average heat transfer coefficient of unsteady impinging jets. Variations in the dimensionless average Nusselt number at the stagnation point and its surrounding region depend primarily on the signal variation pattern and frequency. The inclusion of jump discontinuities in signals can enhance the average Nusselt number to some extent. Combinational signals of sinusoidal-rectangular and saw-toothed-rectangular configurations achieve heat transfer enhancement over steady jets when the frequency exceeds 10 Hz.

Keywords: periodicity; combinational signal; frequency; impinging jet; Nusselt number

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1. Introduction

Jet impingement occurs when fluid exits a nozzle at a certain velocity under pressure difference and strikes the surface of an object to be cooled or heated. Due to the short flow path and the very thin boundary layer formed in the stagnation zone, jet impingement produces extremely high local heat transfer coefficients. This phenomenon has been widely applied in industrial fields such as aircraft wing de-icing, cooling of high-power electronic components, glass tempering, and metal sheet annealing [1]. Numerous scholars have investigated the factors influencing jet impingement heat transfer [2-4].

With advances in industrial technology, the heat transfer enhancement capability of conventional steady jets has proven insufficient for specific applications. Consequently, many researchers have attempted to enhance turbulence intensity by modifying nozzle structures or utilizing self-excited oscillating jets [3] and precessing jets [4], though reports of effective heat transfer enhancement remain limited. With the development of control technology, researchers have experimented with typical periodic jets to enhance heat transfer [5]. However, different studies have often reached inconsistent or even contradictory conclusions. For instance, Azevedo et al. [6] found that pulsed jets weakened heat transfer by 0-20% compared to steady jets across all frequencies. Many researchers have discovered that the effectiveness of periodic jets depends heavily on jet parameters. Hofmann et al. [7] found that heat transfer enhancement only occurred at high frequencies and small impingement heights. Zhou et al. [8] utilized a mass flow control device to generate typical periodic jets and concluded that unsteady jets exhibit a frequency threshold above which heat transfer enhancement can be achieved. These findings indicate that the factors influencing periodic jet impingement heat transfer are highly complex, warranting further investigation.

This study employs a signal generator to control a mass flow controller, producing periodic combinational signals with adjustable frequency and waveform for impingement heat transfer experiments. The results are compared with those from steady and typical periodic jets.

2. Experimental Parameter Definitions

The experimental system for jet impingement is shown in [Figure 1: see original paper]. The system consists of a high-pressure air source and piping system, mass flow control system, heating plate with electric heating, and data acquisition system. Compressed, filtered, and throttled air passes through a flow meter and mass flow controller before exiting the nozzle to impinge on a heating plate with constant heat flux. The temperature distribution on the plate is captured by an infrared thermal imager with thermal sensitivity less than 0.07°C, and specialized software processes the infrared images to obtain the temperature field and Nusselt number distribution on the heat transfer surface.

The mass flow controller is the core component of this experiment. It can adjust flow rates based on input signals from the signal generator with millisecond-level response, enabling output of arbitrary waveform signals. The flow rate range is 0-179.83 L/min, with maximum response frequency up to 125 Hz.

The impingement heat transfer plate is shown in [Figure 2: see original paper]. Its surface is uniformly covered with electrothermal copper foil strips that provide constant heat flux conditions. The convective heat transfer coefficient h, Nusselt number Nu, and impingement jet Reynolds number Re are defined as:

$$T - T \qquad (2)$$

where q is the heat flux of the transfer plate, numerically equal to the average heating power after accounting for radiation and conduction losses; Q is the mass flow rate of the jet (maintained constant for all combinational signals in this study); is the kinematic viscosity of the cooling air; T_w is the plate temperature; and T_f is the jet temperature.

For periodic signals, frequency is a primary parameter. Other experimental parameters include: nozzle inner diameter $D = 15$ mm, nozzle-to-plate distance $H = 6D$, and constant heat flux of 380 $\mathrm{W/m^2}$.

In addition to frequency variation, this study primarily examines the effects of several combinational waveforms on heat transfer performance. These combinational waveforms are formed by combining sinusoidal (sin), rectangular (rec), saw-toothed (saw), and pulsed (pul) signals, as summarized in .

Table 1. Summary of Combinational Signals

Waveform Combination	Notation
Sinusoidal-Rectangular	sin+rec
Rectangular-Sinusoidal	rec+sin

Waveform Combination	Notation
Saw-toothed-Rectangular	saw+rec
Rectangular-Saw-toothed	rec+saw
Pulsed-Saw-toothed	pul+saw
Saw-toothed-Pulsed	saw+pul

These waveforms exhibit distinct characteristics. The combinational signals include both gradually varying sinusoidal waveforms and saw-toothed signals with constant change rates, as well as stable signals at maximum/minimum velocities and sudden velocity jumps. Investigating the impingement effects of these different variation modes is highly significant.

3. Results and Discussion

3.1. Effect of Waveform on Heat Transfer Experiments were conducted for combinational jets I-IV at constant height ($H/D = 6$) and Reynolds number ($Re = 4500$), with results compared against steady and typical periodic jets, as shown in [Figure 3: see original paper] and [Figure 4: see original paper]. The heat transfer performance of combinational periodic jets falls between that of their constituent waveforms. For gradually varying sinusoidal and saw-toothed jets, combination with rectangular signals enhances heat transfer. This occurs because gradually varying jets have lower turbulence intensity, while signals containing jumps exhibit higher turbulence levels, causing abrupt oscillations that generate strong impingement effects and thin the boundary layer, thereby enhancing heat transfer. However, combinational signals still do not surpass the heat transfer performance of typical rectangular waves. Additionally, heat transfer at 20 Hz is significantly stronger than at 5 Hz, prompting further investigation of frequency effects on the average Nusselt number.

Experiments on combinational waveforms V and VI compared with standard symmetric saw-toothed waves yield the results shown in [Figure 5: see original paper]. The presence of pulsed jumps enhances heat transfer compared to typical symmetric saw-toothed signals. Both combinational waveforms show consistent effects with frequency variation, though the enhancement diminishes as frequency increases.

3.2. Effect of Frequency on Heat Transfer As previously noted, frequency is a crucial factor affecting periodic impingement heat transfer. Figure 6: see original paper and (b) present the radial Nusselt number distributions for combinational waveforms I and III at various frequencies under $H/D = 6$ and $Re = 4500$. The Nusselt number in the stagnation zone and its surroundings gradually increases with jet frequency. When frequency exceeds 10 Hz, both combinational jets achieve superior heat transfer compared to steady jets. This is attributed to shorter boundary layer development times at higher frequencies, resulting in a thinner average boundary layer and improved heat transfer potential.

4. Conclusions

1. Experimental investigation of combinational signal jets with identical average mass flow rates reveals that periodic variations in jet signals can alter the average Nusselt number on the impingement plate. The degree of average heat transfer enhancement depends on the signal variation pattern and frequency.
2. The heat transfer performance of combinational signals falls between that of their constituent periodic signals. While jump discontinuities can increase the average Nusselt number to some extent, they cannot surpass the performance of rectangular signals.
3. Combinational sinusoidal-rectangular and saw-toothed-rectangular jets achieve heat transfer enhancement over steady jets when frequency exceeds 10 Hz.

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