# Prediction of heat transfer coefficient in pulsating flow

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A general empirical correlation has been developed for prediction of the heat transfer coefficient in a heating process for steady and pulsating flow of air through a rigid circular pipe. The pulsating frequency (5–60 Hz) was in sine form, and a combined dimensionless number composed of the Reynolds number and a dimensionless flow frequency was used to correlate thermal behavior with flow parameters. A critical value of $2.1 \times 10^5$ for the combined dimensionless number was noticed. Below this value no significant improvement was obtained. The correlation was found to be general and valid for steady and pulsating turbulent flow heat transfer.

**Keywords:** pulsating flow; heat transfer coefficient; pipe flow; turbulent flow

## Introduction

The enhancement of heat transfer rates by applying reasonable means to increase heat transfer coefficients, especially in gases where heat transfer coefficients tend to be small, is an important field in engineering studies. From a theoretical point of view, pulsing a flow is believed to increase the heat transfer coefficient. Moreover, heat transfer in different pulsatile flow systems has been under investigation since the pulse combustion process showed promising heat transfer enhancement. Investigators have studied heat transfer in various specific pulsatile flow systems, but a comprehensive analysis of the problem has not been done.

Due to a variety of control parameters, previous work showed conflicting findings for the effect of pulsation on heat transfer. The effect usually increases the heat transfer coefficient. In some cases, heat transfer decreases. Where local measurements have been made, it has often been found that simultaneous increases and decreases occur at different positions on the surface.

Martinelli *et al.*[1] investigated heat transfer to a fluid flowing periodically at low frequencies in a vertical heat exchanger, and reported that the Nusselt number was higher than that for the steady flow situation when $300 < \mathrm{Re} < 4500$.

West and Taylor[2] studied the effect of partially damped pulsations from a reciprocating pump on the heat transfer coefficient for water flowing at a steady flow Reynolds number of 30,000 to 85,000 inside a vertical tube of a heat exchanger. Their results showed a 60% to 70% increase in the heat transfer coefficient at 1.6 Hz. Muller[3] reported a decrease in the heat transfer coefficient in the wall region of a turbulent flow. Baird *et al.*[4] investigated the effect of pulsing a fluid in the transitional to turbulent region ($4300 < \mathrm{Re} < 16{,}200$). They reported an enhancement in the heat transfer rate when a turbulent flow was pulsed. Hanby[5] studied convective heat transfer in a gas-fired pulsating combustor, where Re was 6000–16,000 and the frequency of pulsation was 100 Hz. It was shown that maximum improvement in heat transfer occurred at the velocity antinodes, while a decrease in heat transfer was observed at some locations. Recently, Gupta *et al.*[6] studied the effect of varying certain parameters on mass and heat transfer rates. It was concluded that the transfer rates in the laminar pulsatile flow increase or decrease, compared to steady flow rates, depending on values of the frequency and pulsation amplitude.

In order to study the effect of introducing pulsation into a flow on heat transfer, we must consider various parameters. Previous studies have discussed the effect of pulsation amplitude, critical frequency, critical Reynolds number, length-to-diameter ratio, and pulsation method. Lemlich[7] reviewed the effect of variation of some of these parameters. He reported observations on pulsating systems: higher frequencies and amplitudes usually give the best improvements; the effect was greater at low Reynolds numbers than at high Re, and for natural convection than for forced, for most systems avoid the quasi steady state. Momentum studies reported a lower critical Re for pulsing flow than for the steady flows.

The present study is an attempt to find a general heat transfer correlation for pulsating flow in ducts similar to those obtained under steady-state flow.

## Experimental apparatus

The apparatus in Figure 1 consists of a pulsing generator, heating, and natural convection air cooling units. The pulsing unit is composed of a piston cylinder connected to an electric-driven motor with variable voltage. A furnace with an operating temperature range of 200 to 1400°C is used as an air heating supply; other electric heaters were also connected. The hot-air temperatures ranged from 50 to 100°C. A 2-m-long, 0.127-m-diameter copper pipe is fixed for natural convection air cooling. Ten thermocouple points were mounted along the pipe at equal distances (0.343 m), five of the thermocouples were inserted in the pipe to monitor the air stream temperature, and the others were attached to the surface. A blower was used to adjust the airflow rates from the laminar to the turbulent regime. The test section consisted of the middle two sections. Some data was collected for the two sections combined as one. Fluid temperature was measured at the centerline at all sections.

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## Experimental procedure

A steady flow of air is allowed to pass through the heated pipe and is cooled by natural convection. When the steady state was reached (constant temperature), the air temperature and velocity were recorded. This procedure was repeated with variable airflow rates to cover the laminar and turbulent regimes. In the second part of the experiment, after a steady flow of air was realized, the data were recorded and pulsing was introduced for the same airflow rate. Frequency and temperature data were recorded. The procedure was repeated to cover the laminar and turbulent regimes. The Reynolds number was varied from 1000 to 40,000, and the frequency ranged from 5 to 60 Hz.

## Discussion and results

Data collected consisted of fluid and wall temperatures at five positions, flow velocity (Re), and frequency of pulsation ($\omega'$). Since no theoretical correlation is available for the heat transfer coefficient in pulsatile flow, a simple heat balance over the test sections was performed and the heat transfer coefficient calculated by equating radially convected heat to heat loss in the axial direction:

$$Q_{\text{loss}} = Q_{\text{conv.}} \text{ by force} = Q_{\text{nat}}\text{. conv. to room}$$

$$mC_p(\Delta T) = hA(T_f - T_s) = Q_{\text{conv.}} \text{ from wall surf. to room}$$

The amount of heat convected from a horizontal hot tube to stagnant air in a room is well correlated in literature.

For checking the accuracy of measuring equipment and the technique of calculation, a steady flow of air was passed through the system. The heat transfer coefficient was calculated by using the Colburn correlation and the above heat balance. The results are shown in Figure 2. Experimental results were in very good agreement with theoretically calculated values.

Data collected were plotted on a graph of (Nu, Pr) versus (Re, $\omega'$), Figure 3. In a previous study, Al-Haddad[8] showed that for low-pressure systems, the amplitude of fluctuations has negligible effect on the heat transfer coefficient. Thus, amplitude of pulsation was not included in the correlation.

In any forced convection process, the Nusselt number should be correlated to the Reynolds and Prandtl numbers. Frequency and amplitude parameters should also be considered in pulsating flows. In low-pressure systems, such as the ones tested here, the amplitude parameter could be neglected. Hence, the correlations were aimed toward finding a relation such as

$$\text{Nu} = f_1(\text{Re}) f_2(\omega')$$

The dimensionless frequency parameter ($\omega'$) was used in previous investigations[9] to define a critical Reynolds number for pulsating flows. In the present study $\omega'$ and Re were combined because both have qualitatively the same effect on Nu. Hence, the correlation

$$\text{Nu} = f'(\text{Re}\,\omega')\text{Pr}^n$$

was suggested, where $n$ is 0.4 for cooling and 0.3 for heating. Nevertheless, it was clear that a new dimensionless parameter $\text{Re}\,\omega'$ could be used to describe fluid flow in low-pressure pulsating systems.

Inspecting Figure 3 reveals that a critical value $\text{Re}\,\omega' = 2.1 \times 10^5$ exists, such that, beyond this value, Nu increases exponentially.

Different empirical formulas were used to fit the raw data, and the best equation for this analysis was

$$\text{Nu} = \text{Pr}^{0.3}\left[23.0 + \frac{5.6[\text{Re}\,\omega' \times 10^{-5} - 2]^2}{1 + 0.17(\text{Re}\,\omega' \times 10^{-5} - 2)}\right]$$

A correlation coefficient of 0.996 was obtained. This equation has an asymptotic value of $\text{Nu} = 23\,\text{Pr}^{0.3}$ for steady turbulent flow, which is acceptable for gases.

Another set of equations could be used to predict the resulting curve:

$$\text{Nu} = 23\,\text{Pr}^{0.3} \qquad 2 \times 10^4 < \text{Re}\,\omega' < 2.5 \times 10^5$$

$$\text{Nu} = a\,\text{Pr}^{0.3}(\text{Re}\,\omega')^b \qquad 2.5 \times 10^5 < \text{Re}\,\omega' < 10^6$$

where $a = 1.313 \times 10^{-4}$ and $b = 1.086$.

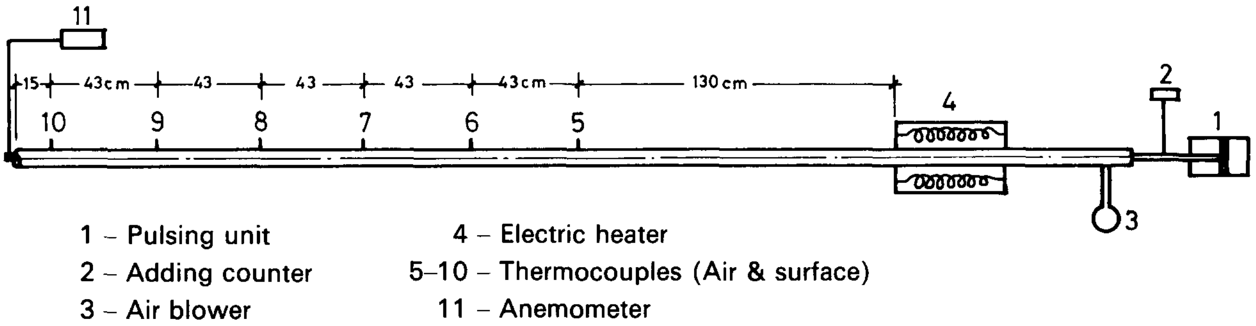

*Figure 1* Schematic of the experimental setup

### Notation

| | |
|---|---|
| $A$ | Surface area of heat transfer in test section, m$^2$ |
| $C_p$ | Heat capacity, kJ/(kg °C) |
| $f_1, f_2$ | Symbols to indicate functions in general |
| $h$ | Heat transfer coefficient, W/(m$^2$ °C) |
| $m$ | Mass flow rate, kg/s |
| Nu | Nusselt number |
| Pr | Prandtl number |
| $Q$ | Heat flow rate, W |
| Re | Reynold's number |
| $T_f$ | Average fluid temp., °C |
| $T_s$ | Average surface temp., °C |
| $\Delta T$ | Temperature difference between outlet and inlet |
| $\omega'$ | Dimensionless frequency, $(\omega r^2/v)^{1/2}$ |
| $v$ | Kinematic viscosity, m$^2$ |
| $r$ | Radius of pipe, m |
| $\omega$ | Frequency, 1/s |

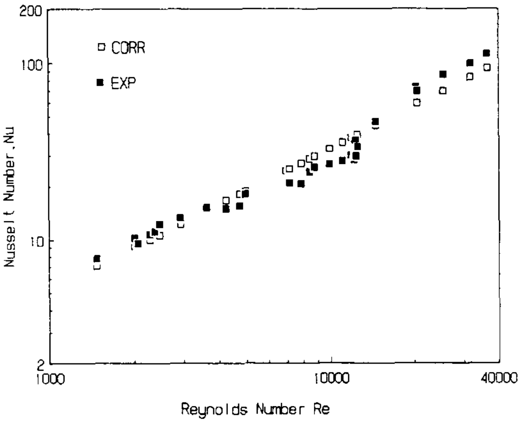

*Figure 2* Comparison of experimental and correlated values

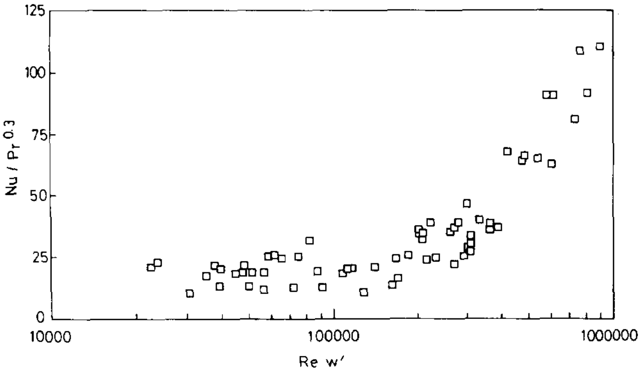

*Figure 3* Heat transfer correlation for pulsatile flows

In conclusion, pulsating a flow in a sine pattern under low-pressure conditions might have no effect or it might increase the heat transfer coefficient, depending on the value of $\mathrm{Re}\,\omega'$. A critical value of $2.1 \times 10^5$ for the combined parameter is observed such that for $\mathrm{Re}\,\omega' < 2.1 \times 10^5$ no significant improvement in Nu occurs, and for $\mathrm{Re}\,\omega' > 2.1 \times 10^5$ the heat transfer is significantly enhanced.

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