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The influence of temperature gradient on the Strouhal–Reynolds number relationship for water and air

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Abstract

This paper focuses on the wake flow behind a heated circular cylinder in the laminar vortex shedding regime. The phenomenon of vortex shedding from a bluff body is an interesting scientific and engineering problem. Acquisition of reliable experimental data is considered an indispensable step toward a deeper physical understanding of the topic.

An experimental study of the wake flow behind a heated cylinder in the forced convection regime is performed using water as the working fluid. Firstly, qualitative visualization experiments were performed and the parallel vortex shedding mode was adjusted. Next, hot-wire anemometry was used for *St–Re* data acquisition. Data analysis confirmed the so-called thermal effect in water: cylinder heating increases the vortex shedding frequency and destabilizes the wake flow.

The effective temperature concept was used and the *St–Re* data were successfully transformed to the $St–Re_{\rm eff}$ curve. Furthermore, a comparison with air as the working fluid was discussed (cylinder heating decreases the vortex shedding frequency in air, thus stabilizing the wake flow). The formula to determine the effective temperature in water was experimentally derived from the present data, while the data and formula for air is already known. The relationship between the Strouhal number and the effective Reynolds number for water and air is represented by the same, universal formula: $St = 0.2660 - 1.0160Re_{\rm eff}^{-0.5}$, where $Re_{\rm eff}$ is calculated at the effective temperature.

Finally, the measurement results were compared to the thermodynamic *St–Re* equation derived by Maršík et al. [F. Maršík, Z. Trávníček, R.H. Yen., A.-B. Wang, Fluid dynamics concept for the critical Reynolds number of a heated/cooled cylinder in laminar crossflow, in preparation]. A satisfactory agreement between the derived equation and experimental data for both fluids (water and air) was achieved.

Keywords: Laminar flow; Vortex shedding; Heated circular cylinder; Effective temperature; Thermal effect

1. Introduction

Fluid flow around a heated bluff body, namely a circular cylinder, is of principal importance for fluid dynamics as well as for heat transfer (see, e.g., [2,3]). The low Reynolds number range, where laminar vortex shedding occurs, is considered very important from a scientific as well as an engineering point of view. The phenomenon of vortex shedding from a bluff body has been studied by many authors – e.g. hundreds of references can be found in the comprehensive monograph by Zdravkovich [4]. This phenomenon is of fundamental importance in the theoretical study of hydrodynamic instability which includes many problems dealing with wake flow dynamics (e.g., [5]), such as the onset of vortex shedding, the passing frequency of vortices, and the influence of geometrical and material parameters. From an engineering point of view, the phenomenon of vortex shedding is considered one of the

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sources of flow-induced vibrations, noise, or even body collapse. It influences drag as well as heat transfer in an external flow.

This paper focuses on the wake flow behind a heated bluff body, namely a circular cylinder in the laminar vortex shedding regime. The heated cylinder is studied in the forced convection regime, as is explained in the following text.

1.1. Thermal effects in air and water for forced convection

The working fluid properties such as viscosity, density and thermal conductivity are fundamentally important for thermal effects. In the text below two of the most common working fluids – air and water – are discussed.

In air, a heat input stabilizes the wake flow, thus laminar vortex shedding can be completely suppressed by heating the cylinder. The onset of vortex shedding (the lower limit of the vortex shedding regime) for an unheated cylinder has been studied many times. The commonly accepted critical Reynolds number ($Re = dU/\nu$, where d is the diameter of the cylinder, U the velocity of the undisturbed flow and ν the kinematic viscosity at the temperature of the undisturbed flow) ranges from 40 to 49 (e.g., $Re_c = 40$ by Kovasznay [6]; 44 by Collis and Williams [7]; 45.9 by Lange et al. [8]; 47 by Fey et al. [9]; 49 by Williamson [10]). Cylinder heating suppresses this onset of instability, thus the Re_c value increases with heating. This increase was evaluated in the range of $Re_c = 47.7$–70 when the cylinder temperature increases to nearly 290 °C [11]. A possible explanation for this thermal effect in air is the increase in kinematic air viscosity with temperature, which causes a decrease in the local Reynolds number. Another known explanation of the thermal effect in air emphasizes the reduction in fluid density with a temperature increase, and thus a reduction in absolute instability [12]. Another approach, based on the analytical description of the variable properties of fluids, was suggested by Herwig and Wickern [13].

If the idea of the so-called *effective temperature* is applied, the onset of vortex shedding even for the case of a heated cylinder can be described by the critical effective Reynolds number $Re_{c,eff}$, which is the same for both heated and unheated cylinders. A value of $Re_{c,eff} = 47.5 \pm 0.7$ was evaluated by Wang et al. [11].

The idea of effective temperature was proposed originally by Lecordier et al. [14], and used later by Dumouchel et al. [15], who worked out this concept and calculated the effective kinematic viscosity ν_{eff} from an effective temperature T_{eff} that is defined by

$$T_{eff} = T_\infty + c(T_w - T_\infty), \quad (1)$$

where T_∞ and T_w are the free-stream and cylinder surface temperatures, respectively. Recently, the effective temperature was derived by Wang et al. [11] in the following form

$$T_{eff} = T_\infty + 0.28(T_w - T_\infty). \quad (2)$$

A recent numerical study by Shi et al. [16] concluded that the effective temperature defined by Eq. (2) [11] agrees well with their results [16].

It is obvious that a quite opposite situation occurs in water, where the kinematic viscosity decreases with temperature. Therefore, cylinder heating destabilizes the wake flow in water. This was confirmed experimentally by Lecordier et al. [17]. However, a lack of adequate experimental data for quantitative confirmation (or adaptation) of the T_{eff} concept for fluids other than air is evident.

It is worth mentioning that the effective temperature is not "just an artificial value", like the well-known film temperature, which is defined as the arithmetic mean of the wall and free-stream temperatures: $T_\infty + 0.5(T_w - T_\infty)$. The effective temperature is close to the hot recirculation zone temperature according to Dumouchel et al. [15]; furthermore the maximum temperature in the wake measured by Yahagi [18] was apparently very close to the effective temperature according to the calculation by Wang et al. [11]. However, no consistent and reliable experimental confirmation of this idea has been published in the available literature thus far, a fact that is one of the main motivations of this study.

The dynamics of the wake behind a bluff body is commonly quantified by means of the Strouhal number (St, denoting a non-dimensional frequency: $St = df/U$, where f is the flow frequency). For the St–Re relation of the isothermal case, several equations have been presented in the literature, e.g., [19,20,9]. The influence of heating on the frequency of vortex shedding was studied recently in air, and it was concluded that the vortex shedding frequency decreases with increasing cylinder temperature. This frequency decrease was quantified by means of the effective temperature concept. When Re_{eff} is evaluated at T_{eff} defined above in Eq. (2), the derived relationship St–Re_{eff} is found to be "universal", i.e. valid for both heated and unheated cylinders [11]:

$$St = 0.2660 - \frac{1.0160}{\sqrt{Re_{eff}}} \quad (3)$$

A recent numerical study by Shi et al. [16] uses the results of Wang et al. [11] as the reference experimental data for the heated cylinders. Shi et al. [16] concluded that the experimental data [11] agree well with the numerical results [16], [21], and that their numerical results [16] confirm the experimental findings of the effective temperature (Eq. (2) [11]).

It can now be assumed that this (or a similar) relation is valid for vortex shedding in water as well, where the cylinder heating (logically) increases the frequency of the shedding of vortices. However, no studies have focused on this problem.

It is worth noting that a precise evaluation of the St–Re curve is intrinsically complicated if the wake is under the influence of the so-called end effects caused by the end conditions of the tested cylinder. Under these circumstances, the vortex shedding from the cylinder is not parallel but