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On the effective temperature concept for liquid: Paradox of the similarity? ☆

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ABSTRACT

The problem of vortex shedding behind a heated cylinder for diluted gasses can be solved by reducing to an isothermal case by means of introducing some effective temperature T_{eff} and based on the similarity condition $Re_{C,\infty}=Re_{C,eff}$. Different situation occurs for liquids. At first sight the similarity should exist since the cylinder cooling stabilizes wake flow. Finding the value of c for liquids represents serious experimental problems therefore, still question remains: there exists a similarity for liquids or not? Here we once and for all give answer that for water the similarity, in aforementioned sense, does not exist. Moreover, more general statement has been formulated based on obtained results: if the kinematic viscosity of a fluid tends to fall as temperature increases the similarity does not exist.

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1. Introduction

Vortex shedding from a circular cylinder has been frequently studied and considered as a basic and representative case of the vortex shedding from a bluff body. Great parts of investigations were focusing on the isothermal case (e.g., Kovasnay [1], Roshko [2], Williamson [3], Fey et al. [4]). Comparatively, the study on the non-isothermal case is apparently few and so that less is known, despite its large practical importance (cf. Zdravkovich [5], Noto et al. [6]).

As suggested by Lecordier et al. [7] and Dumouchel et al. [8], the problem of vortex shedding behind a heated cylinder for diluted gasses can be solved by reducing it to an isothermal case by means of introducing some effective temperature $T_{eff}=T_\infty+c(T_W-T_\infty)$, where c is a constant $\in$ [0 and 1], T_∞ and T_W being the free-stream and cylinder surface temperatures, respectively. Rewriting T_{eff} as $T_{eff}=(1-c)T_\infty+cT_W$ it is easy to see that T_{eff} is a simple linear interpolation between two points T_∞ and T_W. Introducing the effective Reynolds number that employs a kinematic viscosity at the effective temperature, the temperature effect on vortex shedding can be accounted for. This approach assumes that the critical effective Reynolds numbers are the same for both unheated and heated cases [7]. According to Lecordier et al. [7] this condition can be written as follows:

$$\mathrm{Re}_{C,\infty} = \mathrm{Re}_{C,eff}, \tag{1}$$

where $\mathrm{Re}_{C,\infty}=U_Cd/\nu_\infty$ and $\mathrm{Re}_{C,eff}=U_Cd/\nu_{eff}$, respectively. The critical values Re_C and U_C are defined as the lower values of Re and U at the onset of laminar vortex shedding. For heated cylinders, the critical velocity U_C and, correspondingly, $\mathrm{Re}_{C,\infty}$, is a function of T_W and T_∞.

Wang et al. [9] found a value of $c=0.28$ for air in the range $1\le T_W^*\le 2$ ($T_W^*=T_W/T_\infty$) from the condition $\mathrm{Re}_{C,\infty}=\mathrm{Re}_{C,eff}$. The critical Reynolds number was $\mathrm{Re}_{C,\infty}=47.5\pm0.7$. Practically this c-value was found by minimizing over c the root mean square deviation of $\mathrm{Re}_{C,eff}$ from $\mathrm{Re}_{C,\infty}$. To investigate the physical mechanism behind the effective temperature concept, Shi et al. [10] carried out extensive numerical experiments. Their results confirm the experimental finding of Wang et al. [9].

Fedorchenko et al. [11] have shown that the thermal effect in diluted gasses, where cylinder heating stabilizes wake flow (thus delaying the onset of vortex shedding), can be quantified in the extraordinary compact form of the proportionality between the critical Reynolds number $\mathrm{Re}_{C,\infty}$ and the dimensionless film temperature $T_f^*=[(T_\infty+T_W)/2]/T_\infty$. The proportionality $\mathrm{Re}_{C,\infty}\sim T_f^*$ concentrates the thermal effect in the term T_f^* completely, while $\mathrm{Re}_{C,\infty}$ is defined from upstream material properties only. It has been proved the universal character of the proportionality: the linear increase of the critical Reynolds number is independent on the specific material properties for all diluted gasses. Moreover, it has been shown that the effective kinematic viscosity and, correspondingly, the effective Reynolds number can be determined for any dilute gas even without knowing the particular c value. Namely, the value $\nu_{eff}=\nu(T_{eff})$ is expressed through a priory known parameters:

$$\nu_{eff} = \nu_\infty(1+T_W^*)/2 = \nu_\infty T_f^*. \tag{2}$$

Then, the temperature dependence of the critical velocity is determined by:

$$U_C(T_{W^*}) = U_C(1)T_f^*, \tag{3}$$

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