International Journal of Heat and Mass Transfer 119 (2018) 665–677

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

# Direct numerical simulation of energy separation effect in the near wake behind a circular cylinder

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ARTICLE INFO

*Article history:*
Received 2 October 2017
Received in revised form 17 November 2017
Accepted 27 November 2017

*Keywords:*
Energy separation
Total enthalpy
Unsteady vortex flows
Near wake
Boundary layer
Time-averaged flow
Thermally insulated cylinder
Navier-Stokes equations

ABSTRACT

Based on direct numerical simulation of two-dimensional Navier-Stokes equations, the effect of energy separation in unsteady vortex flows is investigated with the reference to the problem of a compressible viscous flow past a thermally insulated circular cylinder. The range of Reynolds ($Re \leqslant 10^3$), Prandtl ($0.1 \leqslant Pr \leqslant 10$) and Mach ($M \leqslant 0.6$) numbers considered corresponds mainly to the periodic vortex shedding regime. The energy separation, associated with the vortex shedding process, manifests itself in the appearance of cold and hot (in terms of total temperature) spots in the near wake. The main attention is focused on the comparative analysis of different mechanisms of total-enthalpy variation in a fluid particle moving around the cylinder, such as the action of viscosity, thermal conductivity, and unsteadiness of the flow. It is shown that the time-averaged total-enthalpy stratification in the boundary layer is caused by dissipative mechanisms. In the vortex formation region and in the vortex street, a decrease in the time-averaged total enthalpy is attributable mainly to the streamline oscillations. The known Eckert-Weise effect of low equilibrium temperature at the rearmost stagnation point of the cylinder is associated with the non-uniformities in the temperature and density fields, created by the evolution of recirculation zones near the body surface. For both instantaneous and time-averaged flow patterns, the regions of local increase and decrease in the total enthalpy are distinguished. It turned out that, in the time-averaged flow, the region responsible for the total-enthalpy decrease in the vortex formation zone does not affect the decrease in the total enthalpy in the developed vortex wake, and vice versa.

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## 1. Introduction

The interest in the process of energy separation in compressible gas flows is associated with the practical need for devices capable of separating a gas flow into cold and hot streams (with low and high total temperatures) without mechanical work or external heat supply. For the first time, such a device was proposed in the early 1930s by Ranque and was called a vortex tube (Ranque-Hilsch vortex tube) [1]. A review of later research on Ranque-Hilsch vortex tubes can be found in [2]. A Ranque-Hilsch vortex tube may ensure an appreciable difference in the stagnation temperatures of the outlet cold and hot streams but has a serious disadvantage associated with too high losses of the total pressure. An alternative scheme of machine-free energy separation, the so-called Leontiev tube [3,4], is devoid of this disadvantage but ensures much smaller efficiency of energy separation. This scheme is based on heat transfer between high-speed (usually supersonic) and low-speed (subsonic) streams having identical stagnation parameters and separated by a thin wall with a low thermal resistance. At present, different methods of enhancing the efficiency of scheme [3] are under study. Among them are: the use of a perforated partition wall, a slot or distributed gas injection or suction on the wall, the creation of a relief on the wall, addition of an admixture of small droplets evaporating in the supersonic boundary layer [5], etc. The main aim of all these methods is to reduce the recovery temperature in the high-speed boundary layer, which then may result in an increase in the heat fluxes through the partition wall and enhancement of energy separation.

In this regard, of substantial interest is the well-known Eckert-Weise effect of low recovery temperature on the rear part of the surface of a thermally insulated cylinder immersed in a compressible gas flow, detected experimentally in the early 1940 [6].

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https://doi.org/10.1016/j.ijheatmasstransfer.2017.11.133
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**Nomenclature**

| | |
|---|---|
| $M$ | Mach number |
| $\mathcal{P}, \mathcal{A}, \mathcal{Q}$ | contributions of non-stationarity, viscous forces, and thermal conductivity in total-enthalpy variation rate |
| $Pr$ | Prandtl number |
| $Re$ | Reynolds number |
| $St$ | Strouhal number |
| $\boldsymbol{n}$ | unit normal vector |
| $\boldsymbol{u}$ | velocity vector $(u, v)$ |
| $\boldsymbol{x}$ | vector of Cartesian coordinates $(x, y)$ |
| $C_D$ | drag coefficient |
| $C_L$ | lift coefficient |
| $c_V$, $c_p$ | specific heats at constant volume and pressure |
| $d$ | cylinder diameter |
| $E$ | efficiency of energy separation |
| $e$ | internal energy |
| $f$ | vortex shedding frequency |
| $I_0$ | normalized total enthalpy |
| $i_0$ | total enthalpy |
| $p$ | pressure |
| $R$ | distance from the cylinder surface |
| $T$ | temperature |
| $t$ | time |
| $U$ | magnitude of the velocity vector |
| $X_{in}, X_{out}, Y$ | distance from the center of the cylinder to the inlet, outlet, and side boundaries of the corresponding subdomains |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | polar angle in clockwise direction, measured from the frontal stagnation point |
| $\Delta$ | approximate size of triangular elements of mesh |
| $\delta$, $\delta_T$ | thicknesses of dynamic and thermal boundary layers |
| $\gamma$ | specific-heat ratio |
| $\kappa$ | thermal conduction coefficient |
| $\mu$ | viscosity coefficient |
| $\rho$ | density |
| $\boldsymbol{\tau}$ | viscous stress tensor |
| $\varepsilon$ | energy |
| $\boldsymbol{\omega}$ | vorticity vector |

*Subscripts*

| | |
|---|---|
| $(\cdot)_{,i}$ | coordinate derivatives, $i = 1, 2$ corresponds to $x, y$ |
| $(\cdot)_{,t}$ | time derivatives |
| 0 | stagnation (or total) parameters |
| $\infty$ | free-stream parameters |

*Superscripts*

| | |
|---|---|
| $'$ | dimensional parameters |
| $*$ | transposition |
| $\overline{(\cdot)}$ | time-averaged value |

The Eckert-Weise effect is commonly associated with a non-stationary vortex shedding process. This connection was suggested by Ryan [7] and since then has been studied in a number of works, most of which were experimental (see, for instance, [7–14]). In an extensive study [9], the authors showed that the intensification of the vortex street (attained by producing acoustic waves in a wind tunnel) decreases the recovery factor at the rearmost point of the cylinder, and based on some numerical calculations they suggested a theoretical explanation of energy redistribution in the vortex street.

The time-averaged flow in the central part of the wake turns out to be cooled and have the total temperature considerably smaller than that in the free stream. With increase in the distance from the body, this effect is being weakened [13]. At the same time, as shown numerically in [9], instantaneous total-temperature distributions contain also fairly well-marked hot spots, which are almost eliminated in the time-averaged patterns [9,13]. The presence of hot spots behind a circular cylinder was also detected in the time-resolved experimental measurements of total temperature [11,14]. The consideration of idealized fluid-particle trajectories and the motion of low pressure regions inside the vortices makes it possible to suggest a simple explanation of the formation of nonuniformities in the time-averaged and instantaneous total-temperature patterns [9]. The key mechanism of the total-enthalpy variation is associated with pressure fluctuations at fixed points of space. In Section 3.1.2, this statement will be confirmed by considering individual fluid-particle trajectories in a vortex street and calculating the total enthalpy using direct numerical simulation.

However, the simple explanation of energy separation in a developed vortex street and the experimentally confirmed connection between the vortex street intensity and the recovery temperature at the rearmost point do not provide a complete explanation of the Eckert-Weise effect. Between these two phenomena (energy separation in the vortex street and the Eckert-Weise effect), there lies the process of vortex formation, which is more complex than the flow in the vortex street, and hence all dissipative mechanisms need to be considered. In Section 3.2, we show that the time-averaged wake can be divided into two subregions with different reasons for cooling: a subregion of a developed vortex street and a subregion of vortex formation. The coldest region turns out to be located in the rear part of the cylinder, where the vortices are formed. To clarify the underlying physics of the effect of decrease in the total temperature in the near wake, including the vortex formation region, is the main aim of our study, which is likely to make it possible to use this effect for improving the efficiency of energy separation devices.

We also aim at giving the quantitative comparison of the contribution of different mechanisms to the energy separation in the near wake on the basis of direct numerical simulation of compressible viscous flow around a cylinder. From the equation of total-enthalpy variation in a fluid particle, it follows that energy separation can be caused by three mechanisms [10]: non-stationarity of the flow (pressure variations at fixed locations), the thermal-conduction effect, and the work of the viscous forces. As will be shown below (Section 3.2), in the time-averaged equation for the total enthalpy a new term (mechanism), associated with the time averaged convective derivative, appears. We will analyze the role of different mechanisms in the energy separation effect for both instantaneous and time-averaged flow fields over a fairly wide range of Reynolds ($30 \leqslant Re \leqslant 10^3$), Mach ($0.1 \leqslant M \leqslant 0.6$), and Prandtl ($0.1 \leqslant Pr \leqslant 10$) numbers.

Our study is based on direct numerical solution of the Navier-Stokes equations obtained with a controlled accuracy by the Galerkin least-squares (GLS) finite-element method on unstructured triangular meshes (Section 2). The results (Section 3) are divided into two parts. In Section 3.1, we discuss the reasons for the variation of the total enthalpy in fluid particles in both

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