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Energy separation in the wake of a cylinder: Effect of Reynolds number and acoustic resonance

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ABSTRACT

Energy separation is a spontaneous redistribution of total energy in a flowing fluid without external work or heat transfer. The energy separation mechanism in the vortex field behind an adiabatic circular cylinder in a cross flow of air is investigated. Time-averaged velocity and temperature measurements taken one diameter downstream of the cylinder ($\mathrm{Re} \sim 10^5$, $M_\infty \sim 0.25$) indicate flow reversal. The measured recovery temperature, expressed as distribution of energy separation factor indicates that energy separation is caused by the vortex flow in the wake, enhanced by acoustic excitation, and is insensitive to Reynolds number in the sub critical range studied.

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1. Introduction

Since energy separation was first observed inside a vortex tube by Ranque [1], it has been studied for various flow situations: laminar and turbulent boundary layers [2,3], resonance tubes [4], shear layers [5], free jet flows [6–8], impinging jets [9–11] and vortex streets behind bluff bodies [12–14]. In case of free jets and flow behind bluff bodies, it is commonly believed that unsteady moving vortices cause energy separation.

1.1. Mechanism of energy separation

Eckert [15] explained the existence of energy separation with a model of a clockwise rotating vortex being convected from left to right. It consists of a viscous vortex core and an inviscid outer region. As shown in Fig. 1, the swirling velocity of the vortex is V_w and the convective velocity is V_0. The dimensionless total temperature inside the vortex is $(C_p\,(T_t - T_{t,\infty})/V_0 V_\mathrm{w})$, where $T_{t,\infty}$ is the total temperature far away from the vortex center. Thus, the total temperature in the upper half of the vortex is greater than $T_{t,\infty}$ and it is lower than $T_{t,\infty}$ in the case of lower half. Fig. 1 shows the velocity pattern and isotherms for the flow around such a vortex. The total temperature maxima are located at the vortex extrema.

A similar model based on the energy equation for inviscid flow without conduction was proposed by Kurosaka et al. [16] (Eq. (1)). Two important points of this model are – (a) the total temperature follows the instantaneous fluctuations in pressure as seen in Eq. (1). (b) The pressure in the center of vortex is lower than outside.

$$\rho C_p \frac{DT_t}{Dt} = \rho \frac{Dh_t}{Dt} = \frac{\partial p}{\partial t} \tag{1}$$

Hence the total temperature of a fluid element following a trochoidal-like path in a vortex street (Fig. 2) starts to fall as it moves from 12 o'clock to 6 o'clock position since the fluid element is approached by the low pressure vortex center. As the vortex passes by the fluid element (6 o'clock–12 o'clock), the pressure rises in the second half of the cycle, raising the total temperature.

These mechanisms are supported by numerical and experimental studies by Han and Goldstein [6,7] and Seol and Goldstein [8] for the case of free jets. The authors measured energy separation factor in the far wake of a cylinder ($3 < x/D < 10$) for a fixed Reynolds number [14] and found that the moving vortex street causes lower total temperature near the wake centerline and higher total temperature near the wake limits.

1.2. Flow reversal in the near wake of cylinder

The flow over a circular cylinder forms an unsteady laminar wake at a relatively low Reynolds number ($\mathrm{Re} \sim 48$) [17]. Beyond this Re, vortices are shed in the wake of the cylinder at a nearly constant non dimensional frequency, $\mathrm{St} = fD/U_\infty$. Numerical and experimental works [18–22] suggest a $\mathrm{St} \sim 0.2$ for $50 \leqslant \mathrm{Re} \leqslant 2.0 \times 10^5$. At this Re, a laminar boundary layer forms on the front

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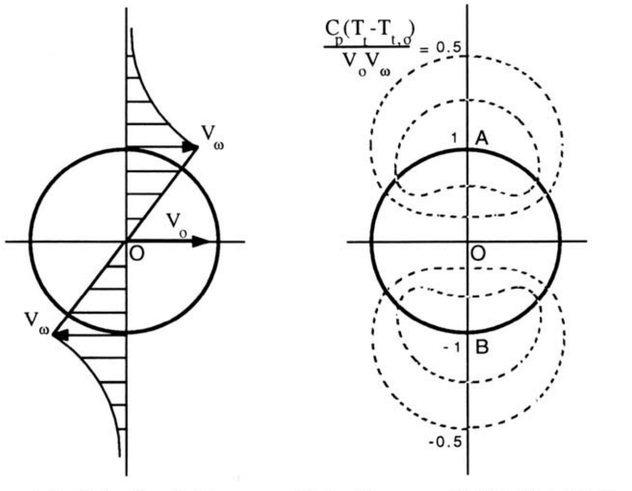
Nomenclature

English	
C_p	specific heat at constant pressure for the fluid [J/Kg K]
D	diameter of circular cylinder [m]
f	frequency of vortex shedding [Hz]
$\dot{H}_{d,\infty}$	enthalpy flow (Eq. (8)) [W]
$\Delta \dot{H}_t$	difference in enthalpy flow between upstream and downstream of cylinder (Eq. (7)) [W]
h_t	stagnation enthalpy per unit mass of fluid [J/Kg]
M_∞	free stream Mach number
$\dot{m}$	mass flow rate at downstream location (x/D = 1) [Kg/s]
$\dot{m}_0$	mass flow rate at upstream location (x/D = −20) [Kg/s]
p	static pressure of fluid [Pa]
Re	Reynolds number ($\mathrm{Re} = U_\infty D/\nu$)
r	recovery factor of temperature probe
S	energy separation factor (Eq. (3))
St	Strouhal number ($\mathrm{St} = fD/U_\infty$)
T_d	local dynamic temperature (Eq. (4)) [K]
$T_{d,\infty}$	dynamic temperature ($= U_\infty^2/2C_p$) [K]
$T_{d,00}$	dynamic temperature in absence of cylinder ($= U_{00}^2/2C_p$) [K]
T_r	recovery temperature measured by the probe [K]
$T_{r,00}$	recovery temperature measured by the probe in absence of cylinder [K]
T_t	total (stagnation) temperature [K]
$T_{t,\infty}$	total (stagnation) temperature at wind tunnel inlet [K]
t	time [s]
U	instantaneous streamwise velocity [m/s]
$\overline{U}$	time-averaged streamwise velocity [m/s]
$\overline{U}_0$	time-averaged streamwise velocity at upstream location (x/D = −20) [m/s]
U_{00}	streamwise velocity in the absence of cylinder [m/s]
U_∞	spatially and temporally averaged streamwise velocity at upstream location (x/D = −20) (Eq. (5))[m/s]
$\langle \overline{U} \rangle$	spatially and temporally averaged streamwise velocity (Eq. (6)) [m/s]
u'	random fluctuations in streamwise velocity (X direction) [m/s]
V_0	convective velocity of vortex [m/s]
V_w	swirling velocity of vortex [m/s]
v'	random fluctuations in cross-stream velocity (Y direction) [m/s]
W	width of test section [m]
w'	random fluctuations in span wise velocity (Z direction) [m/s]
X	streamwise direction
x	distance in streamwise direction from center of the cylinder [m]
Y	cross-streamwise direction
y	distance in cross-streamwise direction from the center of the cylinder [m]
Z	span wise direction
Greek	
ρ	fluid density [Kg/m^3]
θ	angle measured from front stagnation line of the cylinder [°]

of the cylinder surface and flow reversal takes place at $\theta > 90°$. The flow in the far wake of the cylinder is a close approximation of von Karman vortex street described in the models of Eckert [15] and Kurosaka et al. [16]. However, the flow close to the cylinder ($x/D \leqslant 2$) is strongly affected by the cylinder surface and a time-averaged flow reversal is observed. Owen and Johnson [23] using LDV measured the mean and turbulent velocity in the near wake of a cylinder for $\mathrm{Re} = 1.67 \times 10^5$, $M_\infty = 0.6$. The time-averaged measurements show the mean flow reversal in the region $x/D \leqslant 1.3$ with a reverse flow velocity of 25% of U_∞ at $x/D = 1$. Numerical solutions by Catalano et al. [24] using LES and RANS for $\mathrm{Re} = 1 \times 10^6$, show 25% reverse flow velocity at $x/D = 0.75$ and no reverse flow at $x/D = 1.5$, supporting the measured [23] limit on the extent of reverse flow region.

1.3. Energy separation in the flow around a cylinder – effect of acoustic excitation

Eckert and Weise [2] first observed energy separation on the surface of a cylinder in cross flow for $\mathrm{Re} = 1.4 \times 10^5$, $M_\infty = 0.685$. The existence of energy separation was confirmed by Ryan [25] in the wake of a cylinder. In addition, he found that when the frequency of vortex shedding resonated with the first harmonics of



(a) Velocity field (b) Isotherms of $C_p(T_t - T_{t,o})/V_o V_\omega$

Fig. 1. Velocity field and total temperature distribution near a vortex [15].

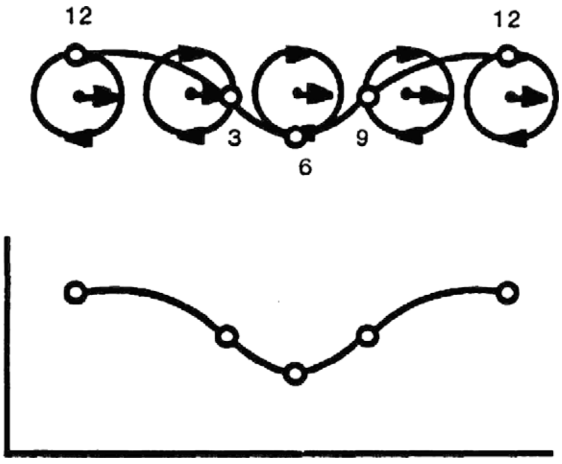


Fig. 2. Variation of total temperature along a path line in a vortex street [16].

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