International Journal of Thermal Sciences 130 (2018) 116–127

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Experimental and numerical study of laminar mixed convection from a horizontal isothermal elliptic cylinder

Wael M. El-Maghlany*, Mohamed A. Alnakeeb, Mohamed A. Teamah, Medhat M. Sorour

Department of Mechanical Engineering, Faculty of Engineering, Alexandria University, Egypt

ARTICLE INFO

Keywords:
Experimental
Numerical
Mixed convection
Elliptic cylinder

ABSTRACT

The problem of laminar mixed convective heat transfer from a horizontal isothermal elliptic cylinder has been experimentally and numerically investigated. The test elliptic cylinder has major and minor diameters of 70.3 mm and 34.9 mm respectively with an axis ratio of 0.496. The buoyancy due to the temperature difference between the cylinder surface and incoming air produces a Grashof number of 2.1×10^6. Via the incoming cold air velocity, the generated Reynolds number varies from 145 to 1322.8. Hence, the corresponding Richardson number is in the range of 1.2–100. The combined effect of both upward natural convection and the forced convection has been executed for angle of attack from 0° (assisting flow) to 180° (opposing flow) with an interval of 30°. The numerical solution via the finite volume method (FVM) has been accomplished to validate the obtained experimental results. The numerical results are validated by previous experimental results which show good agreement. Results are presented in the form of average and local Nusselt number around the circumference of the elliptic cylinder. In addition, new empirical correlation is obtained for the average Nusselt number as a function of Richardson number and the attack angle.

1. Introduction

Fluid flow and heat transfer over a cylinder are very important as they represent the building block of many engineering applications. Cylinders of different cross-sectional shapes (circular, elliptical, rectangular, triangular) [1–6] are used as the main components of heat exchangers, nuclear reactors, and thermal equipment. The circular cylinders obviously have more applications and have been intensively investigated, while elliptic cylinders have been less investigated. When a fluid passes over a stationary body, a region of disturbed flow is always formed around the body which affect the heat transfer. In general, various heat transfer modes may take place ranging from forced convection dominated regime to free convection dominated one. Combined (free and forced) heat transfer mode may also take places when inertia and buoyancy forces are comparable. The local heat transfer features for an elliptic tube set normal to an approaching free stream differs considerably from that of a circular tube. The heat transfer characteristics are strongly influenced by the axis ratio, the angle of attack, and the Reynolds and Grashof numbers.

2. Literature review

Oosthuizen [7] numerically considered assisting mixed, natural and forced convection from horizontal circular cylinders in low Reynolds number flows. The study indicated that the heat transfer coefficient in assisting flow increases over either the purely forced or purely natural convection values in the mixed convection regime. Oosthuizen [8] investigated the limits at which the buoyancy effects should be included in convective heat transfer calculations. The study concluded that the major effect of the buoyancy force is to move the point where the flow is separated from the cylinder. Hatton et al. [9] experimentally investigated mixed, natural and forced convection around horizontal cylinders in a cross flow. The study attempted to determine the lower limit for a forced velocity under which natural convection from a heated hot-wire velocity probe caused significant errors in the heat transfer estimations. Buyruk et al. [10] performed a numerical and experimental study of the laminar flow and heat transfer characteristics of a cross flow. The study was performed for an isothermally heated single circular tube in a duct with different blockage ratios. Abu-Hijleh [11] investigated numerically the laminar mixed convection heat transfer from an isothermal circular cylinder at arbitrary angles of attack of the forced flow by using the finite difference method. The studied parameters were Reynolds number and the attack angles of both assisting and opposing flows. Ibrahim and Gomaa [12] investigated experimentally and numerically the thermo-fluid characteristics of the elliptic tube bundle in cross flow. Their results indicated that increasing

* Corresponding author.
E-mail addresses: elmaghlany@alexu.edu.eg, elmaghlany@yahoo.com (W.M. El-Maghlany).

https://doi.org/10.1016/j.ijthermalsci.2018.04.018
Received 9 March 2017; Received in revised form 11 April 2018; Accepted 14 April 2018

Nomenclature

A	Major radius of elliptic test cylinder, m.
A	cross-sectional area of the elliptic cylinder, m^2
A_d	Inner duct walls surface area, m^2, $A_d = 2\ (W_1+H)\ L_d$
A_{dev}	Epoxy (devcon) area, m^2
A_w	Outer surface area of the test cylinder, m^2
B	Minor radius of elliptic test cylinder, m.
B	Blockage ratio, $B = 2b/H$
C_p	Specific heat at constant pressure, kJ/kg K
C_{pl}	Specific heat of the liquid condensate, kJ/kg K
C_{pv}	Specific heat of the water vapor, kJ/kg K
d_{equ}	Equivalent diameter of Styrofoam insulation inner side, m,
$d_{equ} =$	$1.55\ (A^{0.625} / P^{0.25})$
$D_{c,o}$	Outlet diameter of the Styrofoam insulation, m.
D_{cti}	Inlet diameter of the asbestos rope insulation of the condensate tube, m.
D_{cto}	Outlet diameter of the asbestos rope insulation of the condensate tube, m.
D_p	Inside diameter of the pipe carrying the orifice, m.
$E_{b,dev}$	Emissive power of the black body for epoxy (devcon), W/m^2
$E_{b,d}$	Emissive power of the black body for air duct wall, W/m^2
$E_{b,w}$	Emissive power of the black body for the test cylinder wall, W/m^2
$F_{dev\text{-}d}$	Radiation shape factor from epoxy (devcon) surface to duct walls surface
$F_{w\text{-}d}$	Radiation shape factor from test cylinder wall to duct walls surface
G	Gravitational acceleration, m/s^2
Gr	Grashof number, $Gr = g\ \beta_f (T_w - T_\infty)\ (2a)^3/\nu_f^2$
H	Mixed convection heat transfer coefficient, W/m^2 K
H	Duct height, m
h_{fg}	Condensation latent heat corresponding to the steam pressure, kJ/kg
K	Air thermal conductivity, W/m K
k_{ct}	Thermal conductivity of the asbestos rope insulation of the condensate tube, W/m K
k_f	Thermal conductivity of fluid at film temperature, W/m K
K_o	Flow coefficient
L_c	Length of the Styrofoam insulation, m.
L_{ct}	Length of the asbestos rope insulation wound around the condensate tube, m.
L_d	Duct Length, m.
L_x	Distance from the entrance edge to the test cylinder section, m.
$\dot{m}_a$	Air mass flow rate, kg/s
$\dot{m}_c$	Water condensate mass flow rate and steam mass flow rate, kg/s
Nu_{avg}	Average Nusselt number
Nu	Local Nusselt number
P	perimeter of the elliptic cylinder, m.
p_{atm}	Atmospheric air pressure, N/m^2
Δp_o	The pressure drop across the orifice plate, N/m^2
Pr	Prandtl number
p_s	Static pressure, N/m^2
P_1	Upstream average pressure before orifice meter, N/m^2
$Q_{c,ct}$	Conduction heat transfer from condensate tube to the asbestos rope insulation, W.
$Q_{c,end}$	Conduction heat transfer form test cylinder ends to the asbestos rope insulation, W.
Q_{conv}	Convective heat transfer to the air inside air duct, W.
Q_{rad}	Radiation heat transfer to the inside walls surface of the air duct, W.
Q_{tot}	Total heat transfer from the test cylinder surface, W.
Re	Reynolds number,$Re = U_\infty\ (2a)/\nu_f$
Ri	Richardson number, $Ri = Gr/Re^2$
t	Condensate collected time, sec
T	Local fluid temperature, K.
T_{ci1}	Inside surface temperature of Styrofoam insulation at test cylinder inlet, K.
T_{ci2}	Inside surface temperature of Styrofoam insulation at test cylinder outlet, K.
T_{co1}	Outside surface temperature of Styrofoam insulation at test cylinder inlet, K.
T_{co2}	Outside surface temperature of Styrofoam insulation at test cylinder outlet, K.
T_{con}	Condensate temperature, K.
$T_{c.tub}$	Outside surface temperature of the asbestos rope insulation of the condensate tube, K.
T_d	Duct inside average surface temperature, K.
T_f	Film temperature, K.
T_o	Absolute air temperature downstream of the orifice plate, K.
T_{sat}	Saturation steam temperature, K.
T_{si}	Steam inlet temperature in the test cylinder, K.
T_w	Average outer test cylinder wall surface temperature, K.
T_∞	Air inlet temperature or free stream temperature at the test cylinder section, K.
U_e	Velocity at air duct entrance, m/s
U_∞	Free stream velocity at the test cylinder section, m/s
W_1	Test cylinder length, m
W_c	Mass flow of the water condensate, kg
Z_o	Expansion factor, $Z_o = 1 - 0.2985 \times (\Delta P_o/P_1)$

Greek symbols

β	Coefficient of volumetric thermal expansion of air, K^{-1}
β_f	Coefficient of volumetric thermal expansion at film temperature, K^{-1}
δ_x	Boundary layer thickness at the test cylinder section, m.
ε_d	Emissivity of the inside duct walls surface
ε_{dev}	Emissivity of the epoxy (devcon)
ε_w	Emissivity of the test cylinder surface
μ_f	Dynamic viscosity at film temperature, kg/m s
μ_o	Dynamic viscosity of downstream air in orifice meter tube, kg/m s
υ_f	Kinematic viscosity at film temperature, m^2/s
ρ	Local fluid density, kg/m^3
ρ_e	Air density at the duct entrance, kg/m^3
ρ_f	Air density at film temperature, kg/m^3
σ	Stefan-Boltzman constant = 5.669×10^{-8}, W/m^2 K^4
ϕ	Elliptical coordinates
ψ	Approach or attack angle between forced flow direction and upward vertical direction

the angle of attack clockwise until 90° enhances the convective heat transfer coefficient considerably. The best thermal performance of the elliptic tube bundle was qualified with the lower values of Reynolds number, axis ratio and the angle of attack. Ota et al. [13] measured the local and overall heat transfer characteristics from an elliptic cylinder. The considered parameters were Reynolds number and the attack angle. They found that the lowest value of the mean heat transfer rate was still higher than that for a circular cylinder. Ball and Farouk [14] investigated experimental and numerical studies on the mixed convective flow around a rotating isothermal cylinder. They found that the average