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Vortex heat transfer enhancement in the narrow plane-parallel channel with the oval-trench dimple of fixed depth and spot area

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A B S T R A C T

The article is devoted to the analysis of vortex heat transfer enhancement due to the use of oval-trench dimples. The main role in the understanding of this process is associated with the application of the technologies developed in engineering practice thanks to design decisions. As a result, prevailing interest has been paid to a spherical dimple when a spot diameter is chosen as a characteristic size, whereas hydraulic losses depend on the dimple-to-device size ratio. Progress in vortex heat transfer enhancement due to the use of oval dimples is connected with the explanation of the mechanism of generation of both vortex structures in dimples and spiral vortices behind them. An abrupt increase of heat transfer in the vicinity of the spherical dimple due to the restructuring of the flow structure in the dimple with two vortices to that in the dimple with one spiral vortex made it possible to propose a new shape of a surface vortex generator – an oval dimple located at an angle of inclination to the incoming flow and consisting of two spherical dimple halves separated by a cylindrical insert. The generation of vortex structure in this case is rather stable and intense in comparison to spherical dimple. The numerical results for vortex heat transfer enhancement in the turbulent water flow in the rectangular narrow channel with spherical, 10°-truncated conical and oval dimples of the same spot area and depth at the heated wall are presented. In the article, central attention is given to the mechanism of secondary flow restructuring and heat transfer enhancement due to increase in a relative length and width of an oval dimple followed by the formation of a long spiral vortex in it. The change in the length of the oval dimple (in terms of its width) from 1 to 6.78 allowed one to rationally mount spiral vortex surface generators in the narrow channel with high thermal and thermal-hydraulic efficiencies, significantly exceeding the identical characteristics of channels with spherical and conical dimples. In this case, moderate hydraulic losses in the channel with an oval-trench dimple, when its length is increased to 6.78, are comparable to those in the channel with a basic spherical dimple.

1. Introduction

The topic of heat and mass transfer enhancement due to surface vortex generators – dimples in a remarkable way combines the fundamental and applied aspects of research. Growing interest to this topic is primarily the result of achieving the effect of increasing heat output coefficient at low (as compared to surface protrusions) hydraulic losses. Moreover, it features a wide range of practical applications characterized by a variety of scales (from micro to macro), flow regimes, geometric shapes, and determining sizes of objects under study. Of extreme importance for this topic is the technology of making dimples that in fact predetermine the selection of simple-topology cavities in effort to investigate geometric shapes. Not by chance, the overwhelming majority (more than 90%) of the publications is devoted to heat transfer enhancement due to spherical dimples. The fundamental aspect of vortex heat transfer enhancement is also connected with the fact that it serves as a polygon both for testing the developed and modified semi-empirical turbulence models and for developing the efficient methods of numerical simulation. Over several decades of solution of the dimple problem the way has been passed from industrial design to complex aero-thermophysical design of surface reliefs with the implication of the principles of organization of vortex structures. It has appeared that spherical dimples are not high-performance vortex generators since maximum secondary flow velocities generated by them do not exceed 30–40% of the bulk

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Nomenclature

b	width of an oval dimple, in terms of spot diameter d
C_p	pressure coefficient, $C_p = 2(P - P_{\mathrm{ref}})/\rho U^2$
C_c, C_μ	semi-empirical constants
c_p	heat capacity
d	spot diameter of a spherical dimple (m)
f	friction, $f = \tau_{\mathrm{w}}/\rho U^2$
f_μ	correction function
h	height of a narrow channel, in terms of d
L	cylindrical insert lengthening of an oval dimple, in terms of d
k	kinetic turbulence energy based on U^2
Nu	Nusselt number, $Nu = \alpha d/\lambda$
Nu_{s}	Nusselt number integrated over the dimple region
P	pressure ($\mathrm{N\,m^{-2}}$)
p	pressure based on ρU^2
Pr	Prandtl number, $Pr = \mu c_p/\lambda$
q	dimensionless surface heat flux
$\dot{q}$	surface heat flux ($\mathrm{W\,m^{-2}}$)
Re	Reynolds number, $Re = \rho U d/\mu$
Ri_t	turbulent Richardson number
s	coordinate along the longitudinal middle cross section of an oval dimple, in terms of d
T	temperature, in terms of 293 K
t	coordinate along the transverse middle cross section of an oval dimple, in terms of d
THE	thermal hydraulic efficiency
U	bulk velocity (m/s)
u, v, w	longitudinal, vertical, and transverse velocity components, in terms of velocity U
$\vec{V}$	local velocity vector, in terms of U
x, y, z	longitudinal, vertical, and transverse coordinates, in terms of d
$\vec{x}$	radius-vector

Greek symbols

α	heat transfer coefficient based on the spot area, $\dot{q}/(T_{\mathrm{w}} - T_{bulk})$ ($\mathrm{W\,m^{-2}\,K^{-1}}$)
Δ	dimple depth, in terms of d
ζ	hydraulic loss coefficient
λ	thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
μ	dynamic viscosity coefficient (kg/(m s))
ν	kinematic viscosity coefficient, in terms of Ud
ξ	dependent variable
ρ	density ($\mathrm{kg/m^3}$)
τ	stress ($\mathrm{N\,m^{-2}}$)
χ	oval dimple lengthening, in terms of width b
ω	specific dissipation rate, in terms of U/d

Subscripts

bulk	local bulk temperature
extr	extreme value
f	friction
m	quantity averaged over the wall section strip
min, *max*	minimum, maximum quantities
n	quantity averaged over the projection area of the dimpled section
n_o	quantity averaged over the area of the dimpled section
pl	plane wall
ref	reference value at the inlet
t	turbulent
w	local wall
‘	fluctuation characteristics
1	parameters determined over the 3 × 2 section with the dimple center at the distance of 1 from the front boundary of this section
2	parameters determined over the section surrounding the dimple

Abbreviations

AMG	algebraic multigrid accelerator
BiCGStab	biconjugate gradient stabilized method
ILU0	preconditioner
QUICK	quadratic upwind interpolation for convective kinematics
RANS	Reynolds-averaged Navier-Stokes equations
RLI	Rodi-Leschziner-Isaev
SIMPLEC	semi-implicit method for pressure-linked equations (convenient)
SST model	shear stress transfer model
TVD	total variation diminishing
VP2/3	velocity-pressure, 2D/3D version

velocity. This fact exerts an influence on an attainable heat output value on the windward side of the dimple and in its wake. Moreover, on the inner surface of the spherical dimple weak separated flow zones are characterized by decreased heat transfer in comparison to the plane wall. Therefore, to impart high thermal efficiency to reliefs, very densely packed spherical dimples have been used. As an alternative to spherical dimples, the following approach has been proposed, which was actively developed in effort to design asymmetric oval-trench dimples with a ‘spot area’ of oval shape. These dimples consist of two spherical dimple halves separated by a cylindrical insert. Dimples are located at an optimal angle of inclination of about 45° to the incoming flow in the narrow channel. The preliminary results have shown that oval dimples are capable of producing secondary flows with maximum local velocities of about 80% of the characteristic bulk velocity in the channel. This permits one to consider them as high-performance vortex generators for heat transfer enhancement. This work analyzes the results of vortex heat transfer enhancement and the choice of a rational shape of an oval dimple located at the heated (q = const) wall of the narrow channel. Terekhov’s experimental setup is chosen as a test facility. It is a 2 × 0.33 rectangular channel, whose wall is provided with oval dimples having a different-length insert and a fixed ‘spot’ area, as in the case both of the basic spherical dimple (the spot diameter is equal to 1) and of the 10°-truncated conical dimple, whose shape is close to cylindrical, at a depth of 0.13 (in terms of ‘spot’ area diameter). The lengthening of the oval dimple is varied from 1 to 6.78 in terms of its width. The Reynolds number defined through the spot diameter d of the spherical dimple and the water flow bulk velocity U is taken as equal to 10^4.

2. Heat transfer enhancement in channels with oval dimples

As known [1], one of the promising means to enhance heat transfer in power equipment plants, including in heat exchangers, is to organize discrete roughness on streamlined surfaces. However, when periodic protrusions are located, for example, at the channel wall, a considerable increase in heat output is accompanied by an advanced growth of hydraulic losses. Sometimes this requires that extreme total pressure drops be assigned. It has appeared possible to decrease hydraulic losses when protrusions have been replaced by depressions. It is of importance to note that