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Numerical simulation of the turbulent air flow in the narrow channel with a heated wall and a spherical dimple placed on it for vortex heat transfer enhancement depending on the dimple depth

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ABSTRACT

Numerical study is made of heat transfer enhancement in the narrow channel with insulated walls in air steady flow around a heated spherical dimple, when its relative depth is varied from 0 to 0.26 (in terms of spot diameter) at a defined Reynolds number 4×10^4 based on bulk velocity and dimple spot diameter. The applicability of multiblock computational technologies for solution of Reynolds and energy equations with the implication of an implicit factorized finite-volume algorithm and overlapping different-scale structured grids of different topology, as well as the verification of the shear stress transfer model (SST model) modified with regard to the streamline curvature within the framework of Leschziner–Rodi–Isaev's approach is assessed from the comparison of numerical predictions obtained by different SSTM versions. Flow regimes in a spherical dimple, as its depth is increased, are classified on the basis of the analysis of change in the jet–vortex flow structure in the dimple and its wake in the channel. In what follows, special attention is paid to asymmetric flow around a dimple with the greatest vortex heat transfer enhancement.

1. Introduction

As known [1], one of the promising ways to enhance heat transfer in energy devices, including heat exchangers, is to make discrete roughness at streamlined surfaces. However, when protrusions are arranged periodically, for example, at the tube and channel walls, significant heat transfer enhancement is accompanied by a faster growth of hydraulic losses. Sometimes, to do this, extreme total pressure drops should be assigned. It appears possible to reduce hydraulic losses when protrusions are replaced by cavities. It is also important to note that the relief of discrete roughness at the channel wall is mainly predetermined by the technology of its making. So, most simple technology-made shapes are represented by cylindrical cavities formed by extrusion [2–4]. However hydraulic losses have appeared to be very significant when heat carrier is moving in channels with such cavities. Another rather a simple technological shape of a cavity is hemispherical and it is made by extruding a sphere at a wall, thus causing its deformation. Such cavities attracted the attention of experimentalists [5–8]. Later on, segment-spherical dimples with a relative depth of less than 0.5 (in terms of the dimple diameter) were considered. For example, work [5] revealed the self-similar mode of separated flow in a hemispherical cavity, at whose lateral sides tornado-like structures are formed alternately. Interest of researchers to single cavities was further quickened by the desire to understand the mechanism of tornado-like heat transfer enhancement and to define the shape and geometric dimensions of a dimple rational in terms of thermal and hydraulic efficiency (THE).

A great contribution to the analysis of physical mechanisms of tornado-like heat transfer enhancement on the surfaces with spherical dimples was made by Kiknadze, who proposed the concept of self-organizing tornado-like flows [9] for dimples with smoothed edges, and by Ligrani et al. [10]. A series of the articles of Russian researchers [11–13,7,14,15] should be mentioned among the pioneer experimental works performed in the 90ies of the last century and dealing with turbulent convective heat transfer at a plane wall with moderate-depth spherical dimples, in particular in narrow channels. In view of the retrospective analysis,

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Nomenclature

C_f	friction coefficient, $C_f = 2\tau_w/\rho U^2$
C_p	pressure coefficient, $C_p = 2(p - p_{ref})/\rho U^2$
Nu	Nusselt number, $\mathrm{Nu} = \alpha d/\lambda$
Pr	Prandtl number, $\mathrm{Pr} = \mu c_p/\lambda$
Re	Reynolds number, $\mathrm{Re} = \rho U d/\mu$
T	temperature, in terms of 293 K
U	bulk velocity [m/s]
λ	molecular thermal diffusivity [$m^2\,s^{-1}$]
c_p	heat capacity
d	spot diameter of a spherical dimple [m]
h	height of a narrow channel in terms of d
k	turbulence kinetic energy in terms of U^2
p	pressure [$N\,m^{-2}$]
$\dot{q}$	surface heat flux [$W\,m^{-2}$]
u, v, w	longitudinal, vertical, and transverse velocity components in terms of U
x, y, z	longitudinal, vertical, and transverse coordinates in terms of d
THE	thermal and hydraulic efficiency

Greek symbols

α	heat transfer coefficient based on a dimple spot area, $\dot{q}/(T_w - T_{bulk})$ [$W\,m^{-2}\,K^{-1}$]
Δ	dimple depth in terms of d
λ	thermal conductivity [$W\,m^{-1}\,K^{-1}$]
μ	dynamic viscosity coefficient [kg/(m s)]
ν	kinematic viscosity coefficient in terms of Ud
ρ	density [kg/m^3]
τ	stress [$N\,m^{-2}$]
ζ	hydraulic loss coefficient

Subscripts

bulk	local bulk temperature
f	friction
m	averaged over the protrusion area of the dimple
min, max	minimum, maximum
mo	averaged over the area of the dimple
pl	plane wall
ref	reference value at the inlet
t	turbulent
w	local wall
‘	fluctuation characteristics
_	averaged over the wall section strip

Abbreviations

MSST model	Menter's shear stress transfer model
MUSCL	monotonic upstream scheme for conservation Laws
PIV	particle image velocimetry
QUICK	quadratic upwind interpolation for convective kinematics
SIMPLEC	semi-implicit method for pressure-linked equations (convenient)
SIP	strongly implicit procedure
TVD	total variation diminishing
(U)RANS	(unsteady) Reynolds averaged Navier–Stokes equations
VP2/3	velocity–pressure, 2D/3D version

among the studies made is Terekhov's fundamental work [16] that combined the traditional methods for determination of pressure, heat load and the laser Doppler measurement technique of mean and fluctuation flow velocities in the narrow channel with a single dimple. Ten years later, the results of this work were adopted in effort to study flow characteristics in the narrow channel with single dimples in Rostock, Germany [17]. A detailed review of the articles dealing with heat transfer in single dimples and made before the year 2000 is contained in [18]. At a later time, a series of experimental investigations of vortex dynamics and heat transfer on surfaces with single dimples was supplemented with comprehensive design-experimental research [19–22]. Here it should be noted that these investigations used modern measuring facilities: heat flux gradient sensors and original fluctuation pressure sensors.

Since the early 90ies of the last century, numerical modeling of separated flow around spherical dimples at a plane wall, including calculations of convective heat transfer in channels with single dimples, has been conducting. First, it is necessary to mention the works dealing with solving the Reynolds averaged Navier–Stokes equations closed by the two-parameter dissipative turbulence model [23] with the implication of the factorized finite-volume method [24]. Of interest is the effect associated with medium ejection from the vicinity of small-depth [25] and large-depth [26] dimples in the plane when a low-pressure zone develops inside the dimple. The use of a cylindrical grid with its axis coinciding with the spherical dimple center in the plane allowed jet–vortex structures to be identified on quite small grids [27] in laminar flow around a large-depth dimple followed by the formation of a fan-like jet in the symmetry plane. A further cardinal refinement of numerical predictions of separated flows in dimples is connected both with developing multiblock computational technologies based on different-scale overlaid structured grids of different topology [28] and with using the model of shear stress transfer (MSST) [29]. After updating MSST [30], when in the expression for vortex viscosity the vorticity magnitude was replaced by the strain velocity tensor magnitude, the model was corrected with the regard to the influence of the curvature of streamlines on turbulence characteristics [31] similar to that done in the two-parameter dissipative model with an additional semi-empirical constant $C_c = 0.02$ instead of $C_c = 0.1$ [23].

From the obtained results of numerical modeling of vortex flow around a spherical dimple, including the analysis of heat transfer enhancement, the following should be emphasized: (1) Identification of jet–vortex structures in 3D separated flows with the use of computer visualization methods in the near-wall layer adjacent to a dimple has revealed that tornado-like jets are self-organized on its lateral sides and interact both with the symmetric flow involving two vortex cells or with the asymmetric flow followed by the formation of the monotornado-like flow regime in the dimple [27,29,32,33]. Tornado-like swirled jet flows start at focus-type singularities during fluid spreading over a curvilinear wall. (2) Flow regimes for a dimple and a set of dimples are defined by a great number of geometric and operating parameters, among which a dimple depth, an edge rounding radius, a profile curvature radius (in terms of the “dimple spot” diameter), a channel height and width, a Reynolds number, a turbulence degree, and a scale of external flow are the main characteristics of a spherical dimple. Thus, the problem of designing a surface (relief) rational in terms of heat transfer and hydraulic resistance is multiparameter in character. Interest to flow regime maps is shown by estimators and experimentalists [34–39]. (3) One of the remarkable numerical modeling results is associated with changing the separated flow structure to the symmetric monotornado-like one when increasing the depth of the spherical dimple that causes heat transfer to enhance spasmodically inside the dimple and in its wake. Bifurcation of a vortex structure is stipulated by a level of disturbances