Energy-efficient surface of air capacitors with inclined single-row oval-trench dimples and protrusions

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Abstract. Heat transfer enhancement in the interfin space of an air capacitor due to the use of a package of in-line oval-trench dimples inclined at an angle of 45° to the incoming flow at Re=10³ is numerically simulated. When considering a narrow channel of 1 in height, 80 in length and 4 in width, the case of 31 single-row oval-trench dimples of 0.25 depth is the best. The growth of hydraulic losses does not exceed 46% at an almost 2-fold increase in heat transfer in comparison to the plane-parallel channel.

1. Introduction
Enhancement of heat transfer in the laminar flow in the interfin space of air capacitors [1] is an important practical and scientific problem. To solve it, surface vortex generators [2] are used. Emphasis is made on making inclined oval-trench dimples (OTD) at channel walls [3-9]. Their use in narrow channels allows improving significantly their thermal performance when thermal performance exceeds hydraulic losses. A relative increase in the length of oval dimples turns out to be substantial. It is advisable to select an OTD length of 4 (with respect to width). An inclination angle of a dimple is equal to 45°. Its depth is one of the important factors to provide the thermal-hydraulic performance of dimpled narrow channels. The most substantial performances are achieved at depths of 0.3-0.4 of channel height. The Reynolds number based on bulk flow velocity and channel height is taken equal to 1000. When designing the relief, the packing density of OTDs plays an important role. The recent studies [6-9] have considered the reliefs when dimples are not densely packed at the stabilization length of convective heat transfer in the dimpled channel. A periodic section of the channel with an inclined OTD located in the center of the heated wall was selected. Periodic boundary conditions were determined at the dimple entrance and exit. The task was solved using the correction procedures of pressure and bulk temperature. The effect of a 1.5-fold acceleration of laminar flow and an almost 2-fold increase of heat transfer was revealed.

2. Problem statement, solution method and computational grids
The problem of air laminar flow acceleration (Pr=0.7) and heat transfer enhancement at a defined Reynolds number (Re=10³) in a long narrow channel section, which imitates some part of the interfin space of the air capacitor, is considered. The narrow channel is 84 in length, 4 in width and 1 in height. The control section of length 80 has a package of 31 in-line oval-trench dimples inclined at an angle of
The dimple width is 1, its length – 4.5, its depth in the base case is 0.25, and the edge rounding radius is 0.2 (figure 1,a). The length of a plane-parallel channel section at the entrance and exit in front of and behind the dimpled control section of the channel is set at 2. The step between dimple centers is 2.53. The density of dimples over the control section is quite moderate and is equal to 0.5076. Symmetry conditions are determined at the side channel wall, uniform laminar air flow is at the channel entrance, soft boundary conditions are at the channel exit, the no-slip condition is at the channel walls. One introduces the system of the Cartesian $x,y,z$ coordinates centered at the beginning of the control section of the channel, the $x$ axis is along the channel, the $y$ axis is upward and the $z$ axis is across the channel. All linear sizes are selected with respect to channel height. Cartesian velocity components and the Re number are defined in terms of bulk flow velocity in the channel. Channel walls are isothermal, and a temperature drop is slight: at the dimpled lower wall $T=1.034$ and at the upper wall $T=1$.

![Figure 1. Narrow channel with 31 OTDs (a) and the package of in-line OTDs on the air capacitor fin (b).](image)

The system of the steady Navier–Stokes equations for incompressible medium and the energy equation has been solved using the factorized second-order finite-volume method on different-scale multiblock computational overlapping grids [2-9]. The multiblock technique (MBT) consists in using different-scale, tier and structured overlapping grids consistent with the channel geometry. In two rows of boundary cells of each of the overlapping or overlaid grids, the parameters are determined using the linear interpolation [2] in the same manner as in [10]. In [11], it is shown that the use of this technique is equivalent to the application of adaptive unstructured grids, but with substantially less computing resources, i.e., it is more efficient. This technique also ensures proper accuracy without refining grids since it automatically resolves the entirety of the revealed hydrodynamic features. Computation from grid to grid using the MBT with linear interpolation is a source of errors; however as the test computations of steady circulation flow in a cavity with a movable cover [10] showed, the uncertainty values appear to be quite acceptable. Representation of the convective terms on the implicit side of the transport equation according to the upwind scheme with one-sided differences allows increasing the stability of the computational procedure. To approximate the convective terms on the explicit side of the linearized governing equations, Leonard’s one-dimensional quadratic upwind scheme [12] is adopted. The method of solving algebraic equations is the BiCGSTAB preconditioner [13] with an AMG preconditioner from Demidov’s library (amgl) [14] for pressure
correction and ILU0 for other variables. The VP2/3 (velocity-pressure, 2D/3D) code using the MBT is selected as a base code in this numerical study and is applicable for solution of problems on multi-core computational codes (for example, OpenFOAM).

A multiblock different-scale grid is designed by overlapping particular different-topology grids. A Cartesian channel grid is condensed towards the upper plane wall and the lower curvilinear wall. Longitudinal and transverse steps of this grid are set at 0.07 and the near-wall step is set equal to 0.0005. This grid covers a curvilinear nonorthogonal grid of 0.175 height that matches with the dimpled lower surface of the channel. This grid is more detailed than the base grid. Longitudinal and transverse steps of the grid are of the order of 0.05 and the near-wall step is set at $5 \times 10^{-4}$. The total number of computational cells is 11 millions.

Figure 1b shows one of the cases of the proposed package of inclined two-row OTDs on the air capacitor fin.

3. Analysis of the obtained results
Figures 2-4 and table 1 illustrate some of the obtained results. The packages of nondensely (21) and densely packed in-line base dimples (31) are compared. The package of nondensely packed dimples is similar to the periodic sections of the dimpled narrow channel with one inclined OTD at the center of the heated wall [6-9]. The influence of the OTD depth $\Delta$ on thermal-hydraulic characteristics of the channel (control section-averaged) is assessed: absolute $\text{Nu}_{\text{max}}$, $\zeta$ and relative $\text{Nu}_{\text{max}}/\text{Nu}_{\text{max, pl}}$, $\zeta/\zeta_{\text{pl}}$ (table 1). For $\Delta=0.25$, local relative values of the friction projection along the longitudinal coordinate and of the Nusselt number in the section of the heated wall of the channel at $z=1$ (figure 3) are compared. At last, for $\Delta=0.25$, transverse strip-averaged relative Nusselt number distributions $\text{Nu}_{\text{max}}/\text{Nu}_{\text{max, pl}}$ built along the longitudinal $x$ and transverse $z$ coordinates (figure 4) are compared.

![Figure 2. Packages of inclined nondensely (a) and densely packed in-line (b) OTDs](image)

![Figure 3. Relative values of local friction (a) and the Nusselt number (b) for the packages of inclined nondensely (1) and densely (2) packed single-row OTDs at $\Delta=0.25$.](image)
Making inclined oval-trench dimples at the heated wall of the narrow channel can substantially increase the thermal performance of the device when used for air cooling in contrast to spherical dimples [4,5].

Figures 3,4 show that an increase in the density of dimples of the same depth of 0.25 leads to substantial heat transfer enhancement. For a package of more densely packed OTDs, heat transfer increases with a high rate in the first half of the channel, reaching a local maximum value (of the order of 15) of the relative Nusselt number and an almost 5-fold increase in relative integral heat load averaged over the transverse coordinate. When the number of dimples increases from 21 to 31 over the 80-long wall section, there occurs a 1.5-fold growth of maximum relative heat transfer integrated over the longitudinal strips across the channel (figure 4,b).

It should be noted that the package of widely packed dimples is characterized by a monotonic increase of heat transfer that tends to its value at the stabilization length.

The growth of the dimple depth causes heat transfer to enhance in the channel; a rate of increasing heat transfer is the most substantial in the range of dimple depth from moderate (order 0.2) to large (above 0.3) values. Maximum thermal-hydraulic performance is characteristic of channels with OTDs of 0.25 depth.

A maximum flow velocity \( u_{max} \) in the dimpled channel increases with the dimple depth. For the depth of more than 0.25, the velocity exceeds 2 and correlates with the earlier data [6-9].

The present work analyzes air laminar flow acceleration and heat transfer enhancement in dimpled narrow channels of finite size. Making dimples causes protrusions to appear on the other side of the fin. High protrusions give rise to unsteady flow in the channel and increase hydraulic losses. In the thermal design of a channel with surface vortex generators, a relative protrusion height is chosen.
within 0.1 channel height. The solutions are proposed for packages of air capacitors composed of
dimpled fins and intermediate plates with variable gaps between fins and plates.

4. Conclusion
Numerical simulation of heat transfer is considered in the laminar flow in the interfin space of the air
capacitor, in the finite-size narrow channel with a package of inclined single-row oval-trench dimples
at Re=10³. The channels with nondensely (21) and densely packed (31) OTDs at the 80-long wall for a
channel width of 4 are compared. The influence of the dimple depth on the thermal-hydraulic
performance is assessed. The case of 31 OTDs of depth 0.25 is preferable. The growth of hydraulic
losses does not exceed 46% at an almost 2-fold increase in heat transfer in comparison to the plane-
parallel channel. The solution is offered for packages of air capacitors composed of dimpled fins and
intermediate plates with variable gaps between fins and plates.

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