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Effects of Rib Configuration on Cooling of Gas-Turbine Blades

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Abstract- This study aims to investigate the effects of rib configuration on cooling gas turbine blades. Three-dimensional ribbed square-channel of gas turbine blades are simulated with the Reynolds averaged Navier-Stokes equations. Air flow in periodical transverse and 45º inclined rib arrays, mounted in inline and staggered arrangements on the lower and upper walls of the channel. The governing equations are discretized by the second order upwind differencing scheme, decoupling with the SIMPLE algorithm. The turbulence effect is modeled with the RNG k-ε model. The present numerical results show excellent agreement with published experimental data. The presented results are streamtraces, velocities, local and area-averaged Nusselt numbers over ribbed walls for the Reynolds numbers ranging from 2×10^4 to 4×10^4.

Keywords: heat transfer, numerical simulation, ribbed channel, turbine blade.

Nomenclature

D	Hydraulic diameter of channel (*m*)
h	Rib width (*m*)
H	Channel width (*m*)
k	Thermal conductivity (*W/mK*)
Nu	Nusselt number of a ribbed channel
Nu_0	Nusselt number of a smooth channel
p	Rib pitch spacing (*m*)
Pr	Prandtl number
q	Heat flux (W/m^2)
Re	Reynolds number
T_B	Bulk temperature of flow (*K*)
T_S	Surface temperature (*K*)
α	Rib angle of attack

I. INTRODUCTION

The thermal efficiency of a gas turbine improves as the temperature of the gases produced in the combustion chamber is increased. The upper limit of the combustion temperature is determined by metallurgical advances as well as effective cooling techniques. The materials used to construct rotor blades of gas turbine have a melting point in the range of 1200ºC -1300ºC [1], whereas the temperature of the surrounding gas is well above the melting point of the materials in use. Therefore, the rotor blades require intensive cooling in order to increase the life time of gas turbines. A widely used method for cooling turbine blades is to bleed lower temperature air from the compressor and circulate it within and around each blade. The coolant typically flows through a series of various cross-sectioned shape channels [1].

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Heat transfer enhancement techniques achieve considerable technical advantages and savings of costs [1]. The ribbed cooling channels have been found to be an efficient method of heat transfer enhancement [1-5]. The periodically positioned ribs in a channel interrupt hydrodynamic and thermal boundary layers. Ribs break the laminar sub-layer and create local wall turbulence due to flow separation and reattachment, which reduce thermal resistance and greatly augment the heat transfer [1]. It has been found that if ribs are placed at an inclination angle with respect to the axial direction, secondary flows are induced over the channel, resulting in the rise in the heat transfer rate [1-5]. Although heat transfer is augmented through the use of ribs, the pressure drop (pumping power) of the channel flow is also increased due to the decreased flow area effects [1-5]. Flow and heat transfer characteristics inside the channel of cooling blade of gas turbine depend on flow condition as well as geometric design of the system. Many experimental and numerical investigations have been carried out to determine configurations that produce optimum results of heat transfer enhancement of cooling of gas-turbine blades in terms of thermal performance, pumping power consumption and fabrication effort [2-20]. The investigations illustrated that the cooling channels optimum design are sensitive to many parameters such as:

- channel cross-sectioned shape (square [2, 3, 6] , rectangular [3, 8] , trapezoidal [3], circular [9], triangular [10]);
- channel aspect ratio [3, 5, 8];
- channel sidewall shape (wavy [11]);
- number of ribbed walls in channel (one and two [8], four [12]);
- rib cross-sectional shape (square [2, 3, 5-8], rectangular [4], triangle [13-14], semicircle [14], trapezoidal [14]);
- rib configuration (v-shape [2, 5-7, 15], w-shape [15]);
- rib angle of attack, α [2-6];
- rib width to rip height ratio [16-17];
- rib pitch to rib ratio, *p*/*h* [3, 16-17];
- rib height to channel height ratio (blockage ratio), *h*/*H* [3, 5];
- rib orientation (broken [6], semi-attached [18], detached [19]);
- rib positioning with respect to each other (inline, staggered) [2, 13, 20]; and
- Reynolds number, e.g. [1-3].

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Despite the large volume of studies dealing with square channels with 45º square ribs, some issues still remain unresolved. Moreover, few studies compare the inline and staggered rib arrangements of square ribs [20] and triangle ribs [13]. Promvonge et. al. [20] numerically compared the inline and staggered 45º square ribs in a square channel for laminar flow of Reynolds number between 100 and 1000. Therefore, the present numerical simulations help in explaining the complicated flow field and heat transfer to achieve a better understanding of the ongoing processes of internal cooling channels in a gas-turbine blade. The objectives of this study is to investigate the flow field and heat transfer of inline and staggered 45º inclined rib arrays for turbulent flows with varying Reynolds numbers in the range between 2×10^4 and 4×10^4.

II. NUMERICAL MODEL

The cooling channel of gas-turbine blade under consideration is a square cross-sectioned channel with transverse (α=90º) and inclined (α=45º) ribs as shown in Fig. 1. Rib arrays are mounted in inline and staggered arrangements on the upper and lower channel heated walls. For staggered ribs, the upper heated wall is moved to the right by half the inter-rib spacing, Fig. 1. For a fluid flowing with constant cross-sectioned area, the velocity profile is assumed to be fully developed and independent on the streamwise flow at some distance from the inlet. It is found that, after an entry length of few ribs, the channel flow repeats itself in a periodic behaviour within each rib pitch [3-5]. Moreover, the periodic condition in the streamwise direction is justified once the computational domain is sufficiently large. However, considering the computational source and calculation time, the computational domain with single periodical ribbed channel showed nearly the same results of flow and heat transfer of full-size channel [6]. As a result, the present simulation is limited to a single pitch, Fig. 1. The upstream and downstream boundaries have the same inclination angle as the rib. The coolant, low temperature air bleeding from the compressor, enters the channel and flows over ribs of square cross-sectional shape. The pitch to rib ratio (*p/h*) is 8 and the ratio between rib height and the channel height (*h/H*) is 0.18, Fig. 1. Since the square cross-sectioned rib is the most common in practice today, the majority literature on ribbed channel are mainly focused on this geometry. It is found that among different rib shapes, the square rib produced the best heat transfer performance [14]. The physical properties of the air are assumed to remain constant at the inlet temperature. It is assumed that the incoming flow is in fully turbulent conditions at different uniform velocities, corresponding to Reynolds numbers ranging from 2×10^4 to 4×10^4 within working Reynolds numbers for gas turbine engines [1]. Impermeable boundary and no-slip wall conditions are implemented over the channel walls as well as the ribs. The two opposite ribbed walls are assumed heated surfaces with constant heat flux. The ribs are assumed at conjugate wall (low thermal resistance) conditions. The other two sidewalls are kept adiabatic. These wall conditions are typically encountered in the real cooling of gas-turbine blades [1].

The present numerical simulations have been performed using ANSYS FLUENT 14.5. The channel flow is governed by the Reynolds-averaged Navier–Stokes and the energy equations for three-dimensional, incompressible and steady flow. The body force and radiation heat transfer are insignificant. The selection of the suitable turbulence model is very important in any computational analysis to predict the accurate results. The renormalization group (RNG) k-ε [21] is selected for the present study because it showed the best results among many turbulence models for such stationary ribbed channel flow [2]. The turbulence models are incorporated with a well-established non-equilibrium wall function for the near wall treatment. The governing equations are solved using a finite volume approach with cell centre variable arrangement. The second-order upwind scheme [22] is chosen for momentum and energy equations. The SIMPLE pressure-velocity coupling algorithm is utilized [23]. For the iterative solution of the linearized equations the Gauss-Seidel method is employed with the Algebraic Multigrid solver. The energy equations are solved after the solution of flow and turbulence equations.

In order to capture the spanwise vortices, the full size grids are considered for all studied cases in contradiction to the previous numerical study [2]. The computational domain is resolved by regular Cartesian grids which are refined near the wall surfaces. The y^+ value of the near-wall nodes is kept, in all computations, to less than 10. Considering solution precision and convergent time, the adopted grid size of 209,680 for both inline and staggered ribbed channels produced grid-independent solutions [2]. The solutions are considered to be converged when the normalized residual values are less than 10^{-6} for all variables but less than 10^{-8} only for the energy equation. The Reynolds number, *Re*, is based on the bulk velocity and hydraulic diameter, *D*. The Nusselt number, *Nu*, can be written as:

$$Nu = \frac{q}{\left(T_S - T_B\right)}\frac{D}{k}$$

Where, T_B is the bulk temperature of fluid over the cross section, T_S is the channel wall temperature, q is the heat flux and k is the thermal conductivity. The *Nu* is normalized by Nusselt number for a smooth channel, Nu_0, which is given by Dittus–Boelter formula operated at the same Reynolds number:

$$Nu_0 = 0.023\, Re^{0.8}\, Pr^{0.4}$$

III. RESULTS AND DISCUSSION

The flow structure in the ribbed channel is very complicated due to flow separation, recirculation, reattachment, turbulent mixing, and secondary flow generated by the presence of inclined ribs. Flow structure in the channel with periodical transverse and 45º inclined rib arrays mounted in inline and staggered arrangements can be displayed by considering the streamwise velocity at Reynolds number of 3×10^4 as depicted in Fig. 2. For the transverse ribs, the high streamwise velocity flow is located at the channel centre.

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Meanwhile, ribbed walls exhibit circulation zones. The difference between inline and staggered transverse ribs is that the peak high velocity is continuous for staggered ribs and is broken for inline ribs. However, the inclined ribs modify the streamwise flow field showing less circulation zones near channel walls. The staggered inclined ribs show larger stagnate flow behind ribs. Figure 3 illustrates the effects of the ribs presentation on fluid flow structure using *yz*-plane slices of streamtrace along with spanwise velocity. The slices are taken at the upstream and downstream of the rib along the streamwise direction parallel to the rib. It is worth mentioning that similar contour levels are applied for all slices. It is clear that the spanwise velocity of the transverse cases is negligible and has no effect. The flow adjacent to the upper and lower walls is almost stagnant. However, the presence of the 45° inclined ribs generate very active spanwise motion and creates two cross-stream counter-rotating vortices, aligned with the inclined ribs, which lead to flow mixing between the main and the wall regions. The spanwise velocity near the wall surfaces increases which enhances considerably the heat transfer rate. The secondary counter-rotating vortices carry the hot fluid away from wall surface and bring cold fluid. This indicates the merit of employing inclined ribs over a smooth channel for heat transfer enhancement. It is observed that the secondary cross-stream counter-rotating vortices shrink significantly in the spanwise direction towards the rear sidewall as the fluid flows downstream. The pair of vortices is symmetric for inline ribs; meanwhile, the staggered ribs distort the flow field resulting in more turbulence flow mixing. Figure 4 exhibit contour maps of the normalized Nusselt number (Nu/Nu_0) over the ribbed-wall surfaces for transverse and inclined ribs arranged in the inline and staggered arrangements at Reynolds number of 3×10^4. Similar contour levels and numbers are applied for all maps. Heat transfer enhancement along the ribs topside is attributed to the acceleration of the flow around the ribs due to reduction in channel area. As shown in Fig. 4, the transverse ribs show low Nu/Nu_0 zone at ribs downstream because the fluid flow is nearly stagnant, Fig. 2. This can create overheated zone which may exceed the melting point of the gas turbine material. On the other hand, the cross-stream counter-rotating vortices produced by the 45° inclined ribs provide a significant influence on heat transfer distribution. The vortices induce better fluid mixing between the main flow and the wall sides. The staggered 45° inclined rib shows smaller Nu/Nu_0 zone near the rear sidewall. This can be attributed to that the staggered ribs produce better flow mixing. Figure 5 shows the variation of the area-averaged Nusselt number, Nu/Nu_0, with the Reynolds number over the heated ribbed walls. The present numerical results of inline 45° inclined ribbed channel are compared with the corresponding experimental data of Khamaj [3]. The numerical results predict the overall heat transfer rate in excellent agreement with the experimental results. It shows less than 10% deviation from experimental results due to the large scale motion of the flow field which is not properly reflected in the RNG k-ε turbulence model. However, for all cases, Figure 5 show that the average Nu/Nu_0 decreases with the Reynolds number. It is found ribbed channels can produce average Nu/Nu_0 of about 2.3−3.5 times of the Dittus–Boelter references of smooth channel with no ribs. Therefore, the generation of vortex flows from using ribs as well as the role of better fluid mixing are the reason for the enhancement of heat transfer. This indicates the merit of employing ribs over a smooth channel for enhancing heat transfer. The inline transverse ribs produce 2% higher average Nu/Nu_0 than the staggered transverse ribs. The 45° inclined ribs perform much better heat transfer rate than the ribs placed transversely to the main stream direction. The average Nu/Nu_0 values for the 45° inclined ribs can achieve 20% - 50% higher than transverse ribs depending on Reynolds number, Fig. 5. The numerical computation reveal similar heat transfer rate for both the inline and staggered ribs. However, it was found that the staggered ribbed channel required higher pumping power [2]. However, the selection of the best rib configuration should not only justified by the average Nusselt number. The local Nusselt number should also be inspected to avoid overheated zones.

The streamwise variation of the local Nusselt number, Nu, over the ribbed walls between the ribs at the lowest heat transfer rate zone, namely the rear sidewall, is shown in Fig. 6. The considered cases are 45° inclined inline and staggered ribs for different Reynolds numbers. In general, the presence of the ribs locally reduces the channel area and accelerates the flow around the ribs resulting in heat transfer enhancement over the ribs as demonstrated in Fig. 6. The local Nusselt number shows sharp peak in the downstream tip of the rib. The cross-stream secondary flow which drives the relatively cool air from the channel core toward the wall surfaces reflects on the heat transfer. Figure 6 indicates that the heat transfer is reduced in the vicinity of the rib upstream for both inline and staggered ribs. For inline ribs, the local Nusselt number in the whole channel keeps increasing with the Reynolds number; whereas the heat transfer of the staggered ribs do not affected by the increasing of the Reynolds number. The heat transfer of the low Nusselt number zone in the vicinity of the rear sidewall can be enhanced by using wavy sidewalls [11] or detached ribs [18-19]. However, wavy walls and detached ribs require major fabrication efforts.

IV. CONCLUSIONS

Numerical simulations of fluid flow and heat transfer in square ribbed channels have been investigated. Transverse and 45° inclined rib arrays are set in inline and staggered arrangements on two opposite heated walls. The Reynolds number based on the inlet velocity and inlet hydraulic diameter is ranging from 2×10^4 to 4×10^4. The overall performance of the simulated channels is evaluated and compared. The main findings of this study are summarized as follows:

1. The combined effects of rib angle and rib arrangement considerably affect the Nusselt number distributions over the ribbed walls. However, the ribbed wall area-averaged Nusselt number is almost the same for inline and staggered rib arrangements.

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2. The channel with transverse ribs can reveal 2.8 times higher heat transfer than that of a channel without ribs.
3. The inclined ribs generate secondary flow consisting of two counter-rotating vortices thereby improve the turbulent mixing of the approaching cold fluid and hot fluid near the walls.
4. The presence of 45º inclined ribs can provide 50% higher heat transfer than that of the transverse ribs.
5. However, the inclined ribs exhibit the lowest heat transfer zone at the vicinity of rib upstream near rear sidewall.
6. The mentioned lowest heat transfer zone of inline ribs can be improved by increasing the Reynolds number.
7. The staggered inclined ribs show no significant enhancement of local Nusselt number at the rear sidewall with the Reynolds number.

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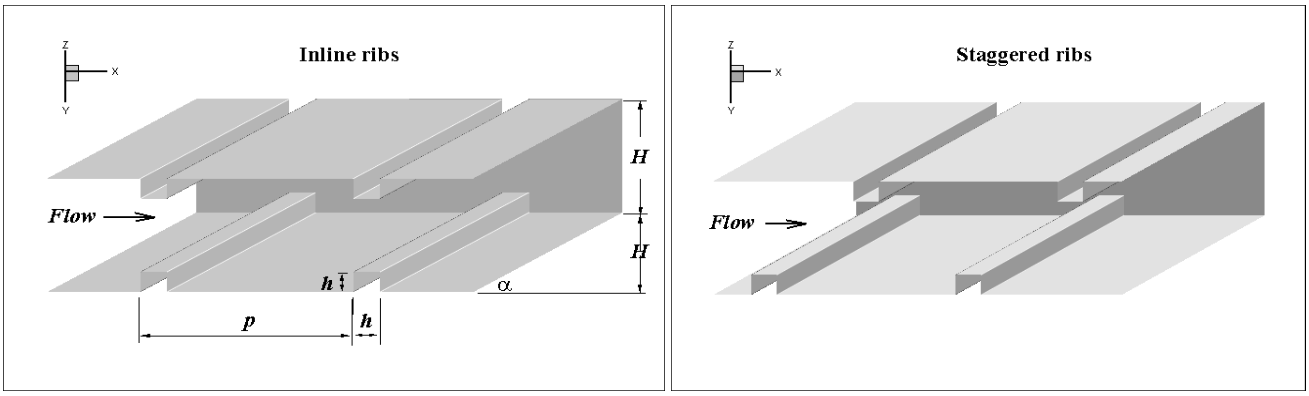
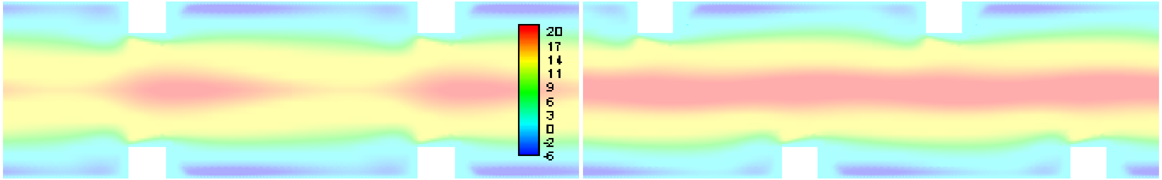
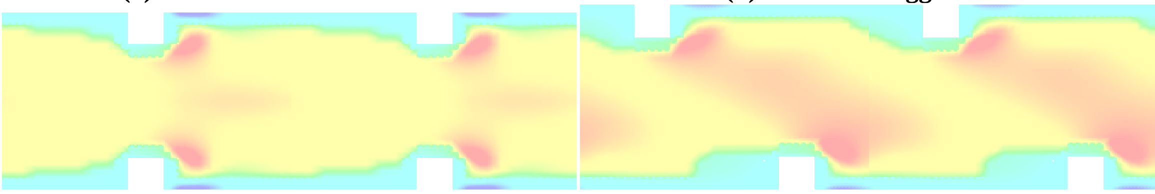


Fig. 1: Computational domains of periodic flow for inline and staggered inclined ribs.

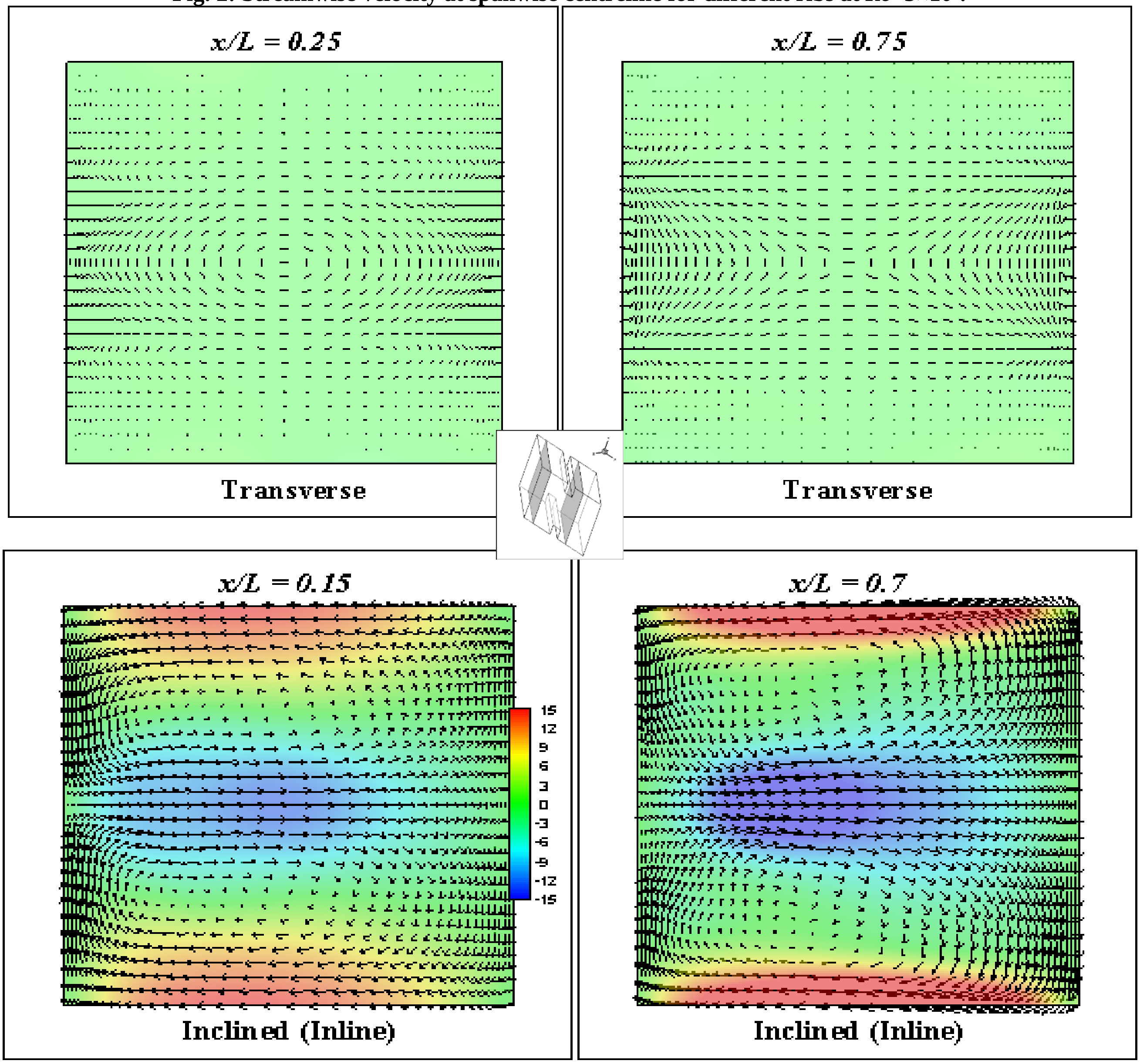


(a) Traverse inline ribs (b) Traverse staggered ribs



(c) Inclined inline ribs (d) Inclined staggered ribs

Fig. 2: Streamwise velocity at spanwise centreline for different ribs at *Re*=3×10^4.



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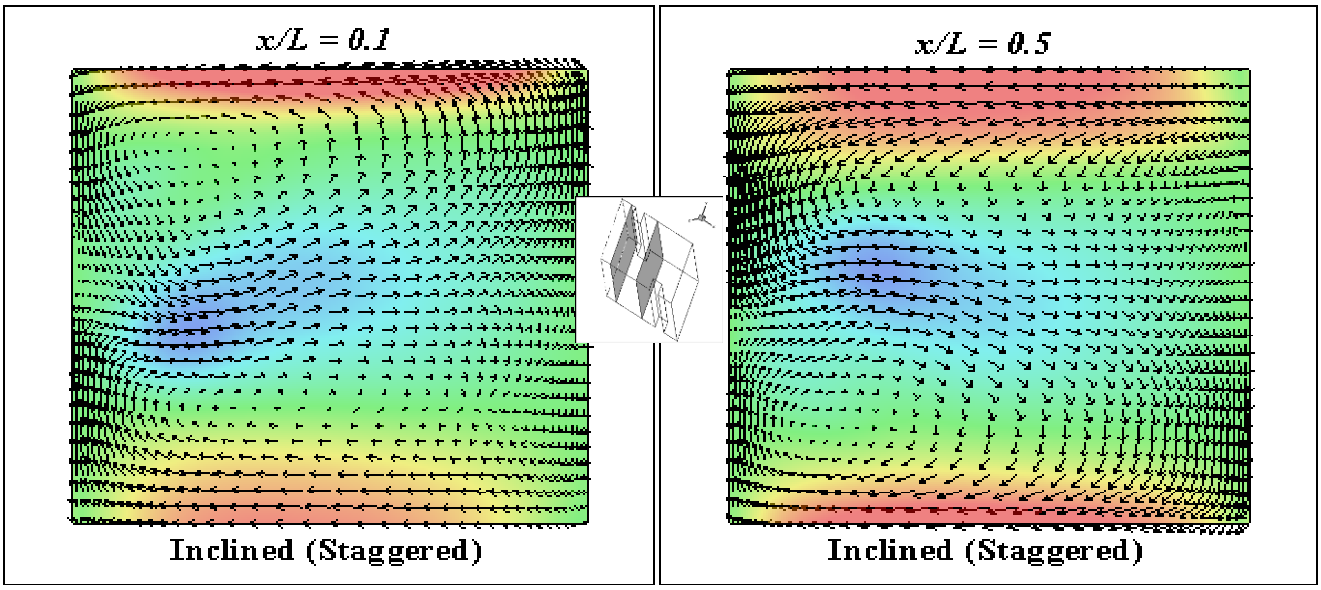

Fig. 3: Streamtraces with spanwise-velocity maps at two streamwise locations (x/L) aligned with the inclined ribs for different ribs at Re=3×10^4.

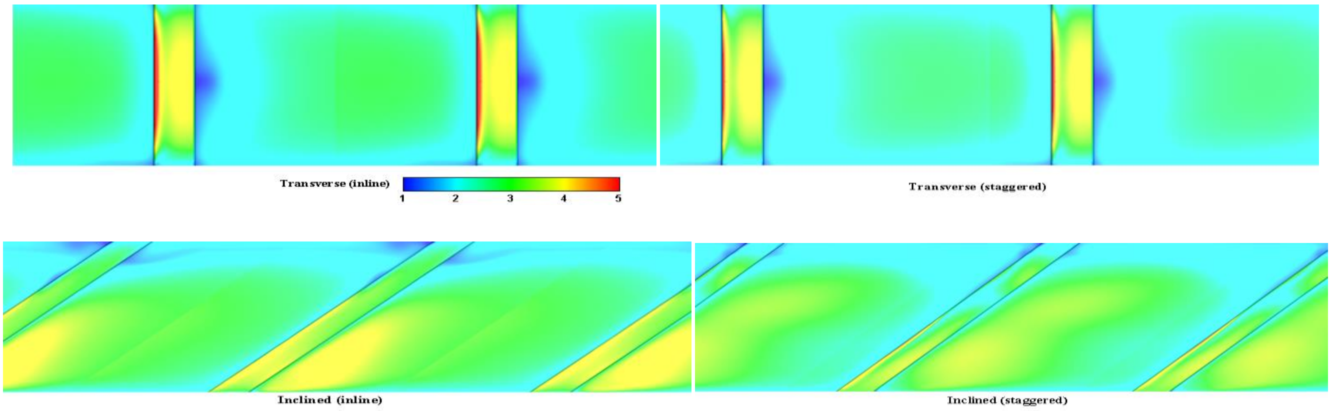

Fig. 4: Ribbed-wall Nusselt number (Nu/Nu_0) maps for different ribs at Re=3×10^4.

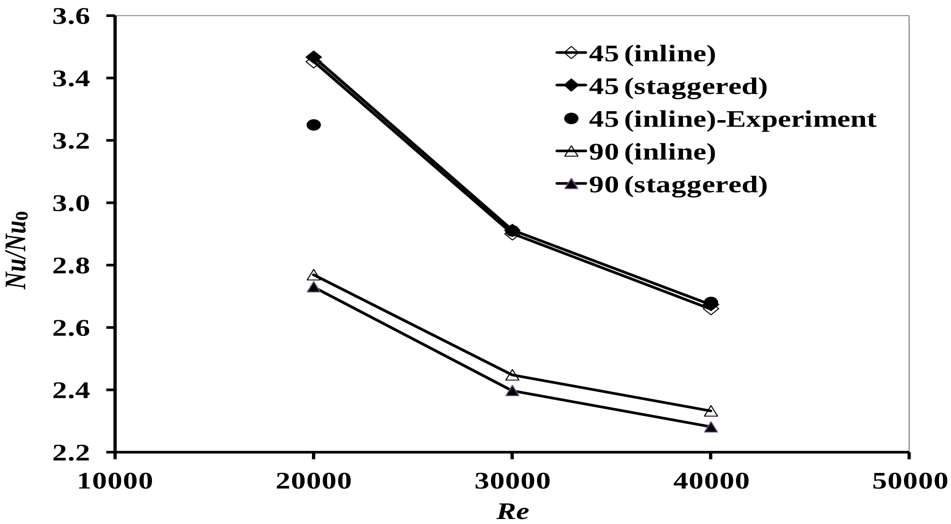

Fig. 5: Variation of ribbed-wall average Nusselt number (Nu/Nu_0) with the Reynolds number for different ribs; compared with the experimental results of inline 45° inclined ribs.

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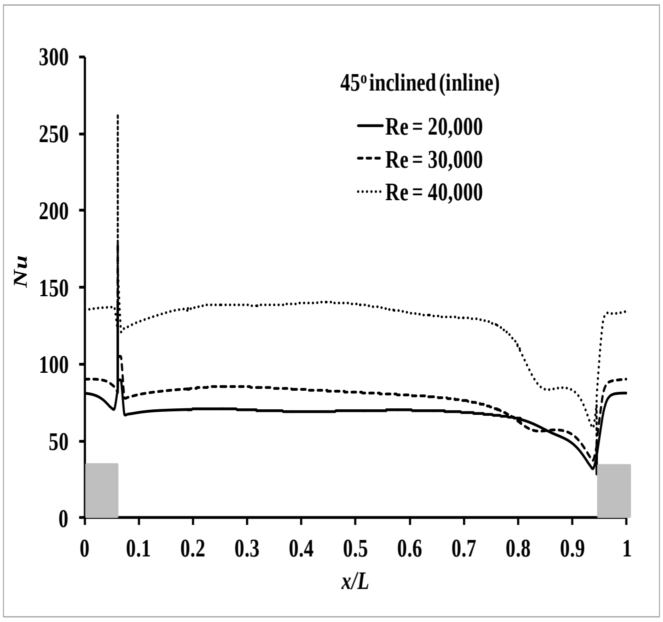

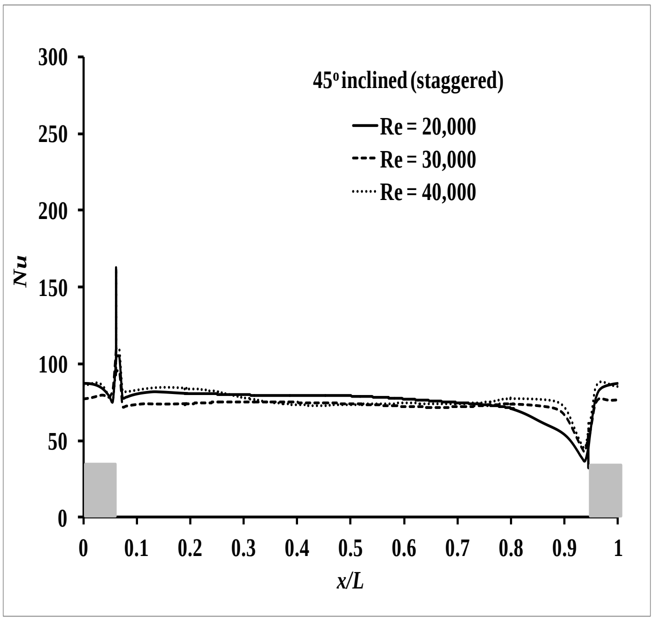

Fig. 6: Variations of ribbed-wall Nusselt number along streamwise near sidewall of the channel for inline and staggered 45° inclined ribs at different Reynolds numbers.

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