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# Characterization of heat transfer enhancement and frictional losses in a two-pass square duct featuring unique combinations of rib turbulators and cylindrical dimples

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Transient heat transfer experiments using liquid crystal thermography have been carried out on a two-pass square channel for testing several unique combinations of ribs and cylindrical dimples. Four different rib shapes, viz. 45° angled, V, W and M have been studied. In compound channels, the rib pitch accommodates cylindrical dimples arranged in the shape of the rib, hence following the direction of rib induced secondary flows. For each rib shape, three different configurations – rib alone, dimple alone and rib–dimpled compound cases were studied. The rib-height-to-channel hydraulic diameter ratio was 0.125 and rib-pitch-to-rib-height ratio was 16. The dimple-depth-to-print diameter ratio was 0.3. The experiments were carried out for a wide range of Reynolds number (19,500–69,000), covering a spectrum typically found in both land-based and air-breathing engines. A total of 52 experiments were carried out to measure detailed heat transfer coefficient on the bottom wall of the two-pass channel. A transient liquid crystal thermography technique was used for heat transfer measurement. Static pressure measurements were carried out to measure the overall pressure drop in the two pass channel. From globally averaged Nusselt number and overall pressure drop, thermal-hydraulic performance of the 13 configurations were determined, compared and analyzed. It has been observed that 45° angled and V compound configurations resulted in higher heat transfer augmentation as well as higher thermal hydraulic performance when compared with their corresponding ribs alone and dimples alone configurations.

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## 1. Introduction

Over the past few decades, increasing demand for higher overall efficiency of gas turbine engines has been pushing the turbine inlet temperatures to higher levels. Such elevated inlet temperatures to the turbine section have the potential to significantly increase the maintenance cost of airfoils, reduce their lifespans or even permanently damage them. In order to develop highly durable turbine airfoils which can withstand extreme thermal loads, innovative internal cooling technologies need to be developed. The present study is an attempt to identify novel heat transfer enhancement features, which are essentially the combination of two separate augmentation techniques. The most commonly used technologies for heat transfer enhancement in internal cooling serpentine passages are rib turbulators, concavities, pin–fins, jet impingement, etc. The present study investigates the heat transfer and pressure characteristics of rib-alone, dimple-alone and rib–dimpled compound channels. Following is a brief outline of some relevant studies reported earlier on rib turbulators, dimples and few very recent studies on the combination of ribs and dimples.

Han et al. [1] presented a detailed overview of the various geometric and flow parameters like rib spacing, their orientation, channel aspect ratio, rib shape etc., which influence ribbed channel heat transfer. Taslim et al. [2] compared the thermal-hydraulic performance of V-shaped ribs, 90° angled, 45° angled and other discrete angled ribs. They observed that the secondary flows generated by the angled ribs contribute to higher heat transfer enhancement compared to 90° ribs. Zhang et al. [3] investigated the effects of compound turbulators on the friction factor and heat transfer coefficient in rectangular channels. The heat transfer performance of rib-groove roughened duct was found to be significantly better than the rib-roughened channel with very little difference in pressure drop characteristics. Mochizuki et al. [4] experimentally studied the combined effects of 180° bend and rib patterns on the heat transfer and friction performance in a two-pass rib- roughened channel. They reported that the arrange-

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**Nomenclature**

| | |
|---|---|
| $c$ | specific heat capacity |
| $d_h$ | hydraulic diameter |
| $f$ | friction factor |
| $f_0$ | friction factor from Blasius correlation |
| $h$ | heat transfer coefficient |
| $k$ | thermal conductivity of test material |
| $k_f$ | thermal conductivity of air |
| $L$ | total length of two-pass channel |
| $\underline{Nu}$ | Nusselt number (based on channel-hydraulic-diameter) |
| $\overline{\overline{Nu}}$ | globally averaged Nusselt number |
| $Re$ | Reynolds number (based on channel hydraulic diameter) |
| $T$ | temperature |
| $t_{target}$ | thickness of the target plate |
| $T_i$ | initial wall temperature |
| $t$ | time taken to reach $T_{tlc}$ |
| $T_m$ | bulk fluid temperature at the inlet on test section |
| TKE | turbulent kinetic energy |
| THP | thermal hydraulic performance |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | normalized wall temperature, $(T_w(t) - T_i)/(T_m(t) - T_i)$ |
| $\rho$ | density |

*Subscripts*

| | |
|---|---|
| $i$ | initial |
| $in$ | inlet |
| $w$ | wall |
| $m$ | mainstream |
| 0 | Dittus–Boelter/Blasius correlation |
| $s$ | smooth surface |
| $x$ | cumulative streamwise distance |

ment of ribs significantly alters the pressure drop and heat transfer performance of the entire channel due to the interactions between the bend-induced secondary flow and rib-induced secondary flow. Ekkad and Han [5] were the first to present detailed Nusselt number distributions for a two-pass square channel using transient liquid crystal technique. Their study provided useful insight into the role of rib induced secondary flow on local heat transfer. Chandra et al. [6] studied the effect of varying number of ribs on heat transfer and friction characteristics of a rectangular channel. They observed a decrease in heat transfer performance with increasing Reynolds number and with each additional rib. Lee et al. [7] investigated the heat transfer distribution in a high aspect ratio rotating ribbed channel with V-shaped and angled ribs and observed that the parallel V-shaped ribs produce the maximum heat transfer enhancement. Jenkins et al. [8] used transient liquid crystal technique to investigate the heat transfer distribution and pressure losses for a ribbed two-pass varying aspect ratio cooling channel with different divider wall-to-tip wall distance. Furthermore, they also studied the effects of bend and rib induced enhancements separately and observed that the bend significantly contributes to the heat transfer enhancement in the outlet channel. Han et al. [9] carried out experiments on different angled crossed ribs and reported that 60° V shaped rib had the highest heat transfer augmentation. Won at al. [10] carried out experiments on 45° angled ribs and reported enhancements (normalized with Dittus–Boelter) from 3.53 to 1.79 times for Reynolds number range of 9000 to 76,000. Tanda and Abram [11] carried out experiments using steady state liquid crystal thermography on 45° angled turbulators for a Reynolds number range from 9000 to 35,500, and reported heat transfer augmentation in the range of 2.7 to 1.8. Steady state liquid crystal thermography technique was used by Tanda [12] to investigate the effects of pitch-to-height ratio of 45° ribs in a rectangular channel with aspect ratio of five. The author reported that a rib-pitch-to-rib-height ($p/e$) ratio of 13.33 was preferable for single wall ribbed case, particularly for higher Reynolds number. In the present study, the rib-pitch-to-height ratio of ribs was chosen to be 16. One reason for this choice is to encounter lower pressure penalties, particularly at high Reynolds number. At lower $p/e$ values, the pressure penalty is significant at high Reynolds number. One aim of present study is to pack the dimples in a ribbed configuration in a particular way so as to achieve higher thermal hydraulic performance. More details on this topic has been presented in later sections. Astarita and Cardone [13] carried out experiments on 30° and 45° ribs using IR thermography for a range of 16,000 to 60,000 Reynolds number. The authors reported low heat transfer augmentation for $p/e = 20$ case, due to more probability of development of boundary layer within a rib pitch.

Several researchers have carried out numerical studies on two-pass channel featuring rib turbulators. The research has been focused on resolving complex flow physics in the sharp 180° turn and the secondary flows induced by rib turbulators. One such study was carried out Murata and Mochizuki [14] where the authors reported Large Eddy simulation (LES) results for the effect of rib turbulators orientation on turbulent heat transfer. In this study, the computational domain included a sharp 90° turn before the coolant flows over rib turbulators in the first pass. This configuration is very similar to the present study's configuration in terms of inlet conditions. The authors reported that the heat transfer in the two pass channel was mainly dominated by the bend induced secondary flows. Lu and Jiang [15] carried out experimental and numerical investigation to study turbulent heat transfer in a rectangular channel featured ribs at different angles to the bulk flow. The SST k-ω turbulence model was chosen and it was concluded that heat transfer increased with increasing Reynolds number and decreasing rib pitch. Jang et al. [16] carried out computations to explore heat transfer and flow field in a two-pass channel featuring ribs inclined at an angle of 60° with the bulk flow. In order to resolve the turbulent flow, a RANS model in conjunction with near-wall second-order RSM with a two-layer k–ε isotropic eddy viscosity model was used. The authors reported that the angled turbulators produced strong anisotropic turbulence due to combined effects of angled ribs and 180° turn, which in turn had significant effect on heat transfer in the second pass. Similar turbulence effects were observed by Jang et al. [17]. Shih et al. [18] carried out numerical investigations to study three-dimensional flow and heat transfer in a U-shaped duct with a square cross-section featuring angled rib turbulators on both the walls. Their study encompassed Reynolds number ranging from 25,000 to 350,000 and the authors also studied the effects of rotation on heat transfer. Due to wide range of Reynolds numbers investigated by the authors, they reported that at lower Reynolds numbers, the bend induced pressure gradients had dominant effects on heat transfer, and at higher Reynolds number – the rib induced secondary flows dominated the heat transfer in the bend and 2nd pass.

In the present compound channel study, the other method of enhancing heat transfer was dimples (also called concavities). Sev-

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