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Review on Dimpled andProtruded Roughness Geometries used in the Duct of Solar Air Heaters

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ABSTRACT

Application ofartificial roughness is considered to be an effective technique for improvingthermalperformance of a solar air heater (SAH).Different types of roughness geometries have been reported in the literature.Among those, the most promising geometries arein the fabricationof dimples and protrusions on the absorber plate. Inthis paper, an attempt has been made toreviewthe dimpled and protruded roughness geometries used in the duct of SAHs and Nusselt number (Nu) and friction factor (f)correlations developed by various investigators.Comparative study of thethermohydraulic performance of dimpled and protruded roughness geometries has also been reported and discussed in this paper.

Keywords: *Friction factor, Roughened duct, Nusselt number, Solar air heater,*

I. INTRODUCTION

The demand and consumption of energy have been increasing multifold due to increase in world population, boom in industries, improving theliving standard and economic upbeat. World is heading towards global energy crisis due to degeneration in theavailability of prime energy resources i.e. fossil fuels. Large-scale use of primary energy sources has also created a serious problemofenvironmental degradationwhich has been deteriorating human health very dangerously. Release of a lot of harmful gases into the atmosphere also resulted inacid raining, global warming etc. Now, another energy sources and especially the renewable energy (RE)sourcesarefascinating thecourtesy of inventors and researchers.Out of many RE sources, solar energy is an important and promising renewable energy source which is available freely, non-polluting and massive potential of fulfilling all energy needs. Solar energy has many applications like crop drying, domestic and industrial heating, ventilation and air conditioning (HVAC) system [1].Solar collector is a special kind of heat exchanger that transforms solar energy into thermal energy. In solar collectors, solar air heater is to be considered as cheap, simple in construction and having various advantages in comparison to solar water heater like corrosion and freezing free [2]. The thermal efficiency of SAH is less because of the low rate of heat transfer between the absorber plate and air flowing in the duct of SAH [3]. Thermal performance of solar air heater can be improved by enhancing the convective heat transfer coefficient with the use of artificial roughened absorber plates [4-5].Various authors have carried out a critical review of different rib geometries used for creating an artificial roughness on absorber plate of aSAH [6-9]. Authors have reported the concept of artificial roughness in the literature and first-time use of artificial roughness in heat exchanger devices [10].Among different techniques of creating anartificial roughness on the surface of absorber plate of solar air heater duct, theformation of dimples and protrusions is considered to besimple, an innovative and economic technique [11].In this paper, an attempt has been made to review the dimpled and protruded roughness geometries used in the duct of SAHs and Nu and f correlations developed by various investigators. Comparative study of thethermohydraulic performance of dimpled and protruded roughness geometries has also been reported and discussed in the present paper.

II. CONCEPT OF ARTIFICIAL ROUGHNESS

Thermal performance of SAH is poor because of the low rate of heat transfer between the absorber plate and air flowing through the duct ofSAH. In order to make SAHsparsimoniously viable, their thermal efficiency needs to be enhanced by augmentingthe heat transfer coefficient. In order to achieve higher heat transfer coefficient, it is desirable that the laminar sub-layer formed on thesurface of absorber plate during theflow of air should be broken and flow at the heat transferring surface is made turbulent. This can be achieved by providing artificial roughness on the surface of absorber plate[3-5].However, with roughened absorber plate, excessive power is required to make theflow of air through the duct. In order to avoid excessive friction loss,flow of air should not be unduly disturbed. It is therefore desirable that turbulence must be generated only in laminar sublayer region which is very close to the heat transferring surface. It can be done by keeping theheight of the roughness element small in comparison with the duct dimension [3-9].

III. DIMPLED AND PROTRUDED ROUGHNESS GEOMETRIES USED IN SOLAR AIR HEATER

Formation of dimples and protrusions on the surface of absorber plate to create artificial roughness is considered to be simple, an innovative and economictechnique.Ithas been observed that in dimpled and protruded roughness geometries, friction penalty is less as compared to heat transfer enhancement [6]. Various types of dimpled and protruded roughness geometries used in the SAH ducts, reported by various investigators have been presented and discussed in the present section.

3.1Dimpled roughness geometry

Saini and Verma [12] studied the effect of parameters on heat transfer and friction characteristicsin a roughened duct provided with dimpled roughness geometryas shown in Fig.1 for Reynolds number (Re) range of 2000-12,000. Therange of relativeroughness height (e/D) of 0.018-0.037 and relative roughness pitch(P/e)of8-12 respectively. Authorsreported that Nu and faugmented by 1.8 and 1.4 times as compared to thesmooth duct.Nu and f correlations as function of Re for roughened duct were recommended as follows;

$$Nu = 5.2\times10^{-4}\,\mathrm{Re}^{1.27}(p/e)^{3.15} \times\left[\exp(-2.12)\left(\log(p/e)\right)^{2}\right](e/D)^{0.033} \times\left[\exp(-1.30)\left(\log(e/D)\right)^{2}\right] \quad (1)$$

$$f_r = 0.642\,\mathrm{Re}^{-0.423}(p/e)^{-0.465} \times \left[\exp(0.054)\left(\log(p/e)\right)^2\right](e/D)^{-0.0214} \times \left[\exp(0.840)\left(\log(e/D)\right)^2\right] \quad (2)$$

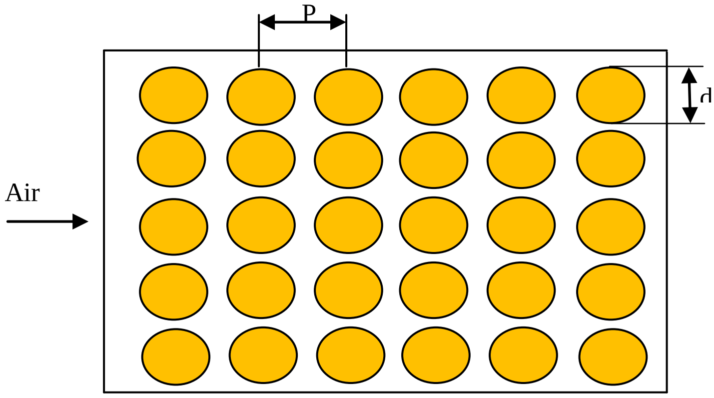

Fig. 1. Absorber plate having dimpled roughness

Sethi et al. [13] studied the effect of dimple arranged in an angular arc shape as shown in Fig. 2 for Re range of 3600-18,000. The range of relative roughness pitch (P/e) of 10-20, relative roughness height (e/D) of 0.021-0.036 and arc angle (α) of 45°-75° respectively. Maximum enhancement in Nu and f as 2.54 and 3 times in comparison to the smooth duct has been reported by the authors.Nu and f correlations as function of Re for roughened duct were recommended as follows;

$$Nu = 7.1\times10^{-3}\times\mathrm{Re}^{1.1386}\times(e/D_h)^{0.3629} \times(p/e)^{-0.047}\times(\alpha/60)^{-0.0048} \times\exp\left[-0.7792\left(\ln\left(\alpha/60\right)\right)^2\right] \quad (3)$$

$$f = 4.869\times10^{-1}\times(e/D_h)^{0.2663}\times\mathrm{Re}^{-0.233} \times(p/e)^{-0.059}\times(\alpha/60)^{0.0042} \times\exp\left[-0.4801\left(\ln\left(\alpha/60\right)\right)^2\right] \quad (4)$$

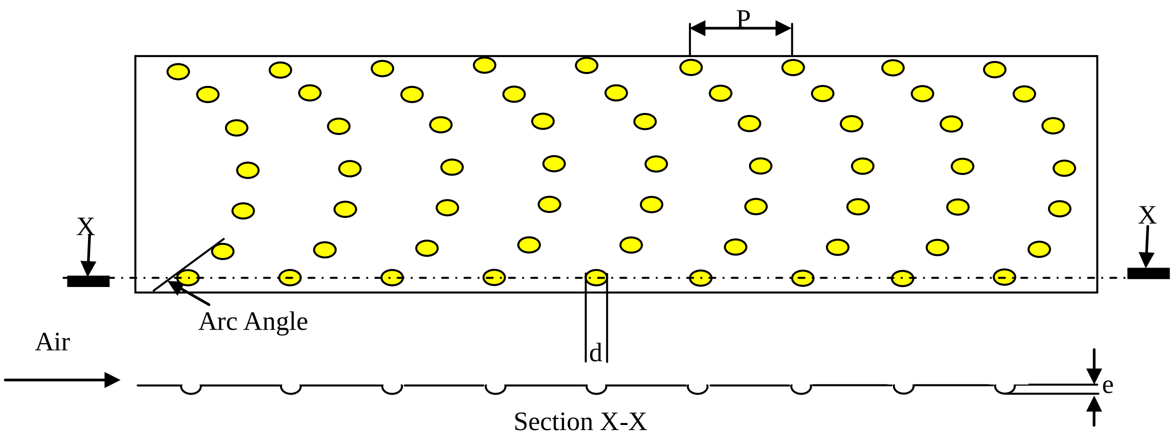

Fig. 2. Absorber plate having dimple arranged in an angular arc shape.

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Kumar et al. [14] studied the effect of multiple V-pattern dimplesas roughness geometry as shown in Fig. 3 forRe range of 5000-17,000. Range of relative dimpled obstacles width (W_c/W_d), dimpled depth to print diameter (e_d/d_d), relative dimpled pitch (P_b/e_d), 8.0-11.0and angle of attack (α_α) was 1.0-6.0, 0.50-2.0, 8.0-11.0 and 35^o-75^o with fixed relative dimpled height (e_d/D_h) of 0.037 respectively.Maximum enhancement in Nuand f as 6.4 and 8 times in comparison to the smooth duct has been reported by the authors. Nu and f correlations as function of Re for roughened duct were recommended as follows;

$$Nu = 9.35\times10^{-14}\,\mathrm{Re}^{1.065}(W_c/W_D)^{2.9832}\times(P_b/e_d)^{2.99} \times(e_d/D_d)^{-0.248}\times(\alpha/55)^{-01.096} \times\exp\left[(-0.91)\ln\left(\frac{W_c}{W_d}\right)^2\right]\times\exp\left[\ln\left(\frac{P_b}{e_d}\right)^2\right] \times\exp\left[(-0.1906)\ln\left(\frac{e_d}{D_d}\right)^2\right] \times\exp\left[(-2.563)\ln\left(\frac{\alpha}{55}\right)^2\right] \quad (5)$$

$$f = 2.05\times10^{-5}\,\mathrm{Re}^{-0.6307}(W_c/W_D)^{0.0853}\times(P_b/e_d)^{19.13} \times(e_d/D_d)^{-0.162}\times(\alpha/55)^{-0.2254} \times\exp\left[(0.0676)\ln\left(\frac{W_c}{W_d}\right)^2\right]\times\exp\left[\ln\left(\frac{P_b}{e_d}\right)^2\right] \times\exp\left[(-0.341)\ln\left(\frac{e_d}{D_d}\right)^2\right] \times\exp\left[(-2.303)\ln\left(\frac{\alpha}{55}\right)^2\right] \quad (6)$$

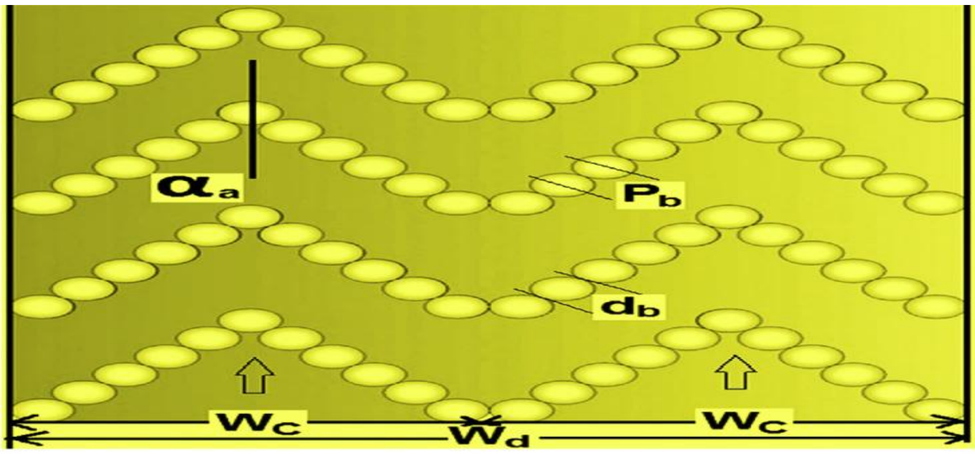

Fig. 3. Absorber plate having dimple arranged in multiple V-pattern shape.

3.2 Roughness geometry in the form of protrusions

Bhushan and Singh [11] carried out an experimental investigation on heat transfer and friction characteristics of a roughened duct having protruded roughness geometry provided on absorber plate as shown in Fig. 4 for Re range of 4000-20,000. The range of relative short way length(S/e) of 18.75-37.50 and relative long way length(L/e)of 25.0-37.5 with fixed relative roughness height (e/D) of 0.03. Maximum improvement inNu and f as 3.8 and 2.2 times in comparison to the smooth duct has been reported by the authors.Nu and f correlations as function of Re for roughened duct were recommended as follows;

$$Nu = 2.1\times10^{-88}\,\mathrm{Re}^{1.452}(S/e)^{12.94}(L/e)^{99.2}\,(d/D)^{-3.9}\times\exp\left[(-10.4)\{\log(S/e)\}^2\right]\times\exp\left[-77.2\{\log(L/e)\}^2\right]\times\exp\left[(-7.83)\{\log(d/D)\}^2\right] \quad (7)$$

$$f = 2.32\,\mathrm{Re}^{-0.201}(S/e)^{-0.383}(L/e)^{-0.484}(d/D)^{0.133} \quad (8)$$

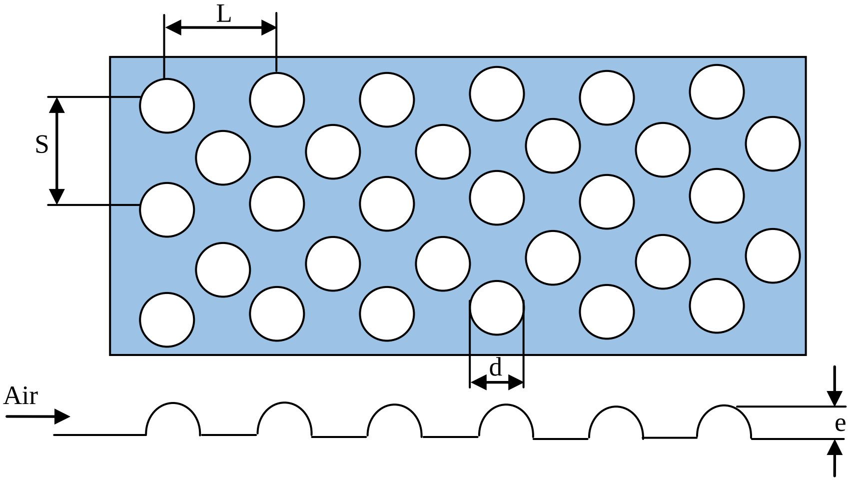

Fig. 4. Absorber plate roughened with protruded shaped geometry.

Yadav et al. [15]reported anexperimental investigation on heat transfer and friction characteristics of SAH duct having protrusions arranged in anarcshape on absorber plate as shown in Fig.5 for Re range of 3600-18,100. The range ofe/D, P/e and α was 0.015- 0.03, 12-24 and 45^o-75^o respectively. Authors reported maximum enhancement in heat transfer and friction factor as 2.89 and 2.93 times in comparisonto thesmooth duct for the investigated range of parameters.Nu and f correlations as function of Re for roughened duct were recommended as follows;

$$Nu = 0.154\times\mathrm{Re}^{1.017}\times(p/e)^{-0.38}\times(e/D)^{0.521}\,(\alpha/60)^{-0.213}\times\exp\left(-2.023(\ln(\alpha/60))^2\right) \quad (9)$$

$$f = 7.207\times\mathrm{Re}^{-0.56}\times(p/e)^{-0.18}\times(e/D)^{0.176}\,(\alpha/60)^{0.038}\times\exp\left(-1.412(\ln(\alpha/60))^2\right) \quad (10)$$

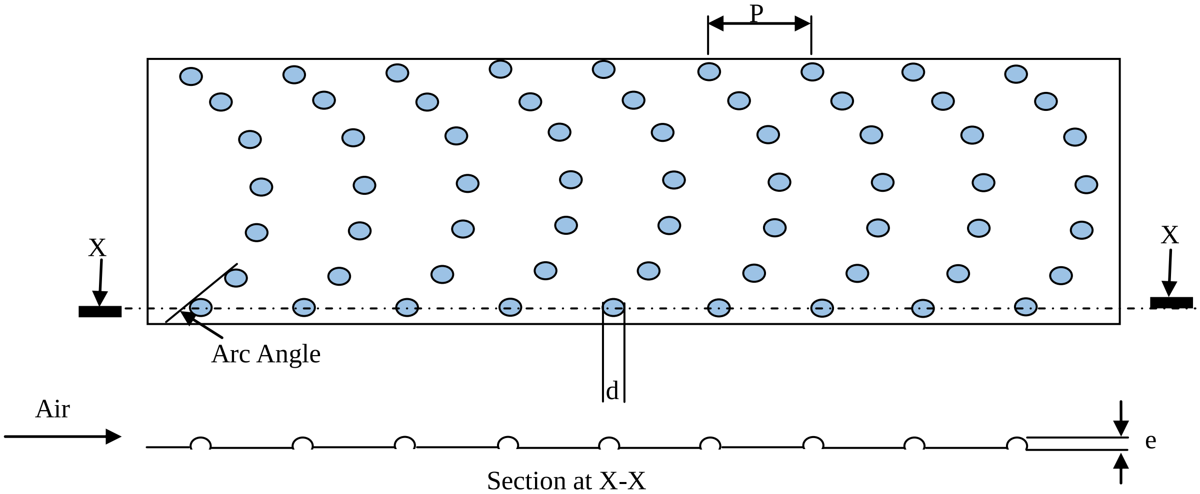

Fig. 5. Absorber plate roughened with protruded shaped arranged in angular arc.

IV. COMPARISON OF DIMPLED AND PROTRUDED ROUGHNESS GEOMETRY

It is required that design of solar airheater should be made in such a way that heat transfer should be maximum with minimum power requirement [6].In order to bring into account the power required for propelling air through the duct, it is more appropriate to evaluate thermohydraulic performance instead of evaluating thethermal performance of a solar air heater. In the present paper, thermohydraulic performance has been evaluated by using the following relationship reported by Jaurker et al. [16].

$$\eta = \frac{Nu/Nu_s}{(f/f_s)^{\frac{1}{3}}} \quad (11)$$

where η = efficiency index

Nu =Nusselt number (roughened duct)

Nu_s = Nusselt number (smooth duct)

f= friction factor (roughened duct)

f_s = friction factor (smooth duct)

Comparison of thermohydraulic performance of dimple and protrusion roughness geometries investigated by different authors has been shown in Fig.6. Thermohydraulic performance has been compared evaluated by using the Nu and fcorrelations for dimple and protrusion roughness geometries.

It can be observed from Fig. 6 that protruded roughness geometry resulted better thermohydraulic performance as compared to that has been resulted by dimpled roughness geometry for the investigated range of parameters.

V. CONCLUSIONS

Inthis paper, an attempt has been made to review the dimpled and protruded roughness geometries being used to enhance the thermal performance of SAHs.

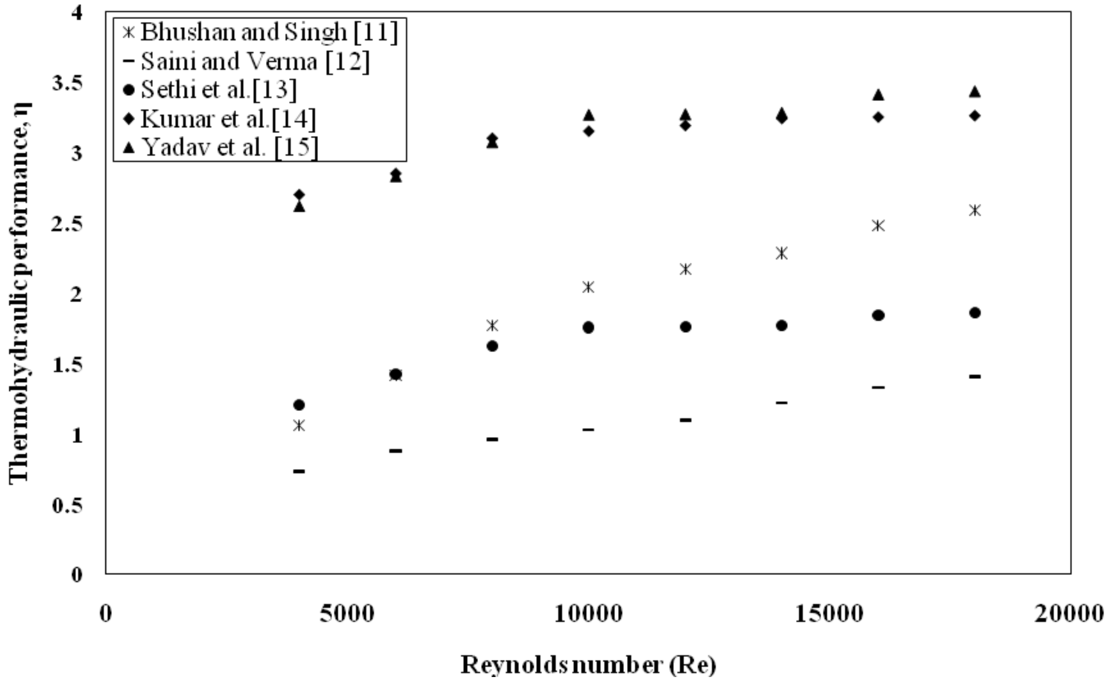

Fig.6. Comparison of thermohydraulic performance of ductroughened with dimples and protrusions.

It is found from the literature that formation of dimples or protrusions on the surface of absorber plate of a solar air heater is considered to be an innovative, simple and an economic technique.Nusselt number and friction factor correlations developed by various investigators for dimpled and protruded roughness geometries have also been reported in this paper. Comparison of thermohydraulic performance of SAH ducts having dimpled and protruded roughness geometries have shown that protruded roughness geometry results in a better thermohydraulic performance.

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