ASTFE American Society of Thermal and Fluids Engineers

4th Thermal and Fluids Engineering Conference (TFEC)
April 14–17, 2019
Las Vegas, NV, USA

TFEC-2019-27879

Heat Transfer and Fluid Flow in A Water-Filled Glass Louver

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ABSTRACT

Numerical studies of water flow and heat transfer in a water-flowing glass louver are conducted for harvesting solar thermal energy. The distribution of absorbed solar radiation in the louver is pre-calculated via the Monte Carlo method. The prismatic louver is surrounded by ambient air and subjected to natural convection. The finite element method based on COMSOL is adopted in the simulation of the three-dimensional steady-state laminar flow and conjugate heat transfer with solar energy absorption. Temperature-dependence is considered of water properties including the dynamic viscosity, density, heat capacity and thermal conductivity. Investigation is placed on thermal energy harvest and storage, flow pattern, pressure drop, and temperature change of the water in the louver. Influence of water flowrate is scrutinized.

KEY WORDS: Solar energy, thermal energy storage, pressure drop, temperature rise, glass louver

1. INTRODUCTION

There is huge amount of solar energy irradiating onto the earth: approximately 3×10^{24} joules per year, most of which remains unutilized while we keep depleting traditional fossil fuels [1]. The integrated spectral irradiance of ASTM E-490 corresponds to a solar constant of 1366.1 W/m^2out the atmosphere [2]. In recent years, the annual installation capacity of solar photovoltaic panels and solar power plants has seen a significant increase worldwide. Yet it is of great interest to explore new ways for effectively utilizing the green and renewable solar energy.

A prismatic glass louver can change the direction of sunlight such that the collimated solar irradiation is directed to the ceiling of a room and scatters diffusely to illuminate the space. This will eliminate the "glare" effect in natural daylighting and increase occupant comfort [3]. When water or a nanofluid is filled and flows inside the hollow louver, the infrared energy of solar irradiation can be effectively harvested and stored as thermal energy in the water or nanofluid. Therefore, a water/nanofluid-filled prismatic glass louver can be utilized to enhance daylighting as well as to harvest solar energy [4].

There are varieties of experimental and numerical studies on the flow and heat transfer of water and nanofluids in channels in the literature. Gupta and Garg [5] predicted the thermal performance of domestic solar water heaters in terms of its geometry and material specification along with its thermal capacity. Mohammed et al. [6] discussed the impact on heat transfer and fluid flow when various types of naofluids such as Al_2O_3, Ag, CuO, diamond, SiO_2 and TiO_2 were used in triangular shaped microchannel heat sink (MCHS). Bianco et al. [7] numerically analyzed the turbulent forced convection of nanofluid in a circular tube with a constant and uniform heat flux at the wall. Using both single and two-phase models the convective heat transfer coefficient with nanofluid is greater than that of base fluid. Tahir and Mital [8] studied the heat transfer of developing nanofluid in a circular channel which is subjected to a uniform heat flux. Wen and Ding [9] performed the experimental study on the convective heat transfer of nanofluids, made of $\gamma - Al_2O_3$ nanoparticles and de-ionized water flowing through a copper tube in the laminar flow regime.

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The absorption and transmittance of solar irradiation through a water-filled glass louver have been studied by Cai and Guo [4] and Cai et al. [10]. Based on the pre-calculated solar energy deposition in the water and glass louver, the fluid flow and conjugate heat transfer in the louver have been investigated in this study. The geometry of the louver and tube is fixed. The variable is the water flow velocity, i.e., the flowrate. Under the same solar irradiation condition, the influence of flowrate on the temperature rise, pressure drop, and thermal energy harvest are scrutinized.

2. SIMULATION METHOD

2.1 Physical Model

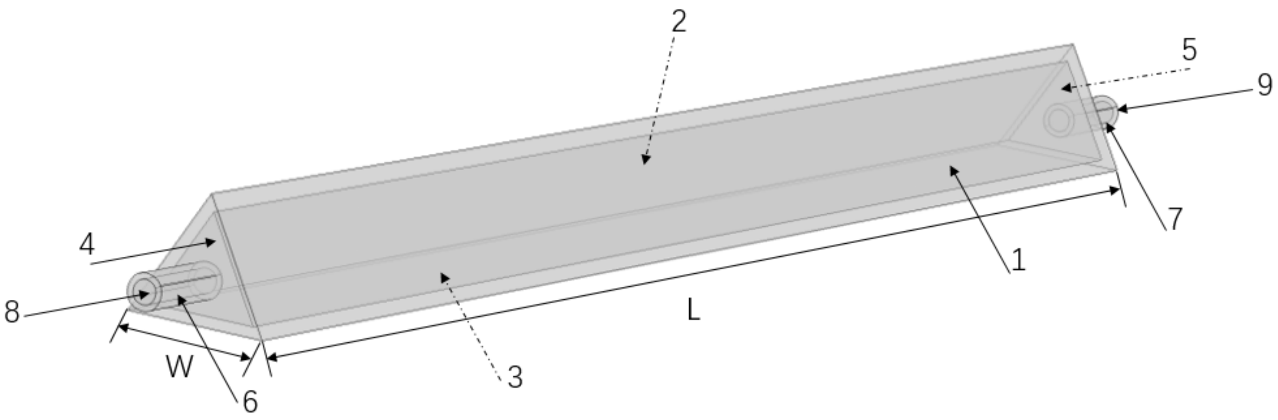

Fig. 1 Sketch of a prismatic hollow louver with connecting tube on both ends.

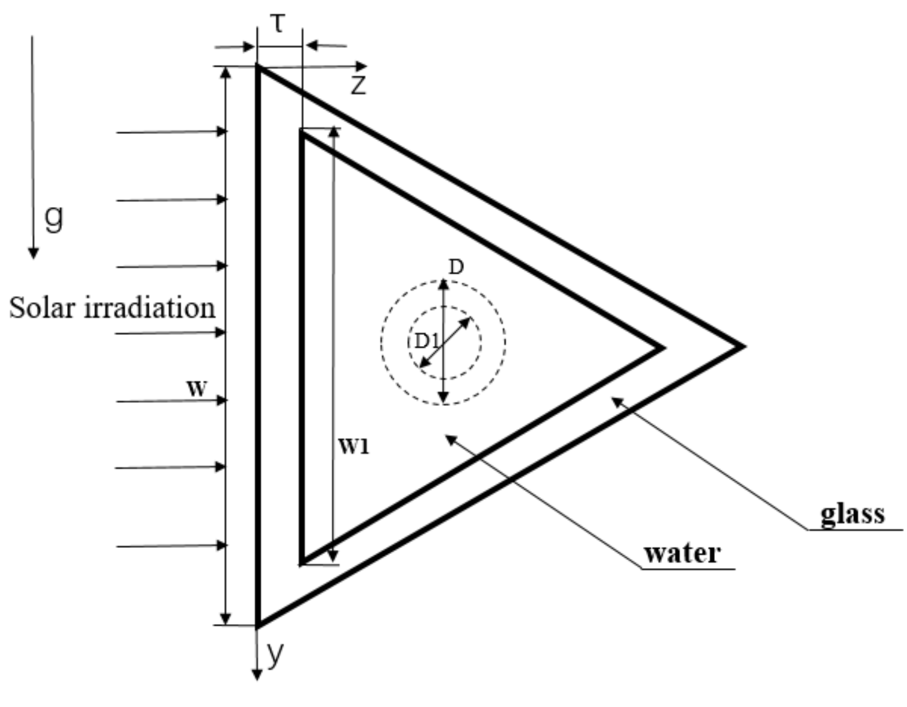

Fig. 2 Side view of a water-filled glass louver.

Figs. 1 and 2 show the physical model and geometry of the water-filled glass louver used in this study. The prismatic louver is built of silica glass. A cascade louver system installed behind a window consists of many louvers connected by copper/rubber tubes. The water flows slowly inside the louver, harvesting and storing the absorbed solar energy into thermal energy. After circulation in a cascade, the water could become very hot. Here we focus on studying water flow and conjugate heat transfer in a single louver with two connecting copper tubes.

In the present study, the length of the glass louver is L = 1 m. The cross-section of the glass louver is an enclosure formed by two equilateral triangles with width W = 0.0762 m (3 inches), W1 = 0.0597 m (2.35 inches), and glass thickness τ = 0.0047625 m (0.185 inch). The length of each copper tube is 0.06 m. The outer diameter of the tube is D = 0.01905 m (0.75 inch) and the inner diameter is D1 = 0.0127 m (0.5 inch).

2.2 The Governing Equations

Steady-state incompressible fluid flow and conjugate heat transfer with temperature-dependent properties are considered in this study. The water flow inside the hollow louver and tube is laminar as its Reynold number considered is less than 2000 even with the largest flowrate studied here. The governing equations are as follows:

Continuity equation,

$$\nabla \cdot (\rho\vec{u}) = 0 \tag{1}$$

Momentum equation,

$$\rho(\vec{u} \cdot \nabla)\vec{u} = \nabla \cdot \left[-P\vec{I} + \mu(\nabla\vec{u} + (\nabla\vec{u})^T)\right] + \rho\vec{g} \tag{2}$$

Energy equation,

$$\nabla \cdot \left(\rho C_p \vec{u}\mathrm{T}\right) = \nabla \cdot (k\nabla T) + q''' \tag{3}$$

In which, ρ, C_p, T, k, $\vec{u}$, P, $\vec{g}$ and q''' indicate the density, heat capacity, temperature, thermal conductivity, velocity vector, pressure, gravity, and absorbed solar energy, respectively. In the glass layers, velocity is set as zero. In the water region, fluid flow is calculated. In both the glass and water regions, solar energy absorption was simulated via Monte Carlo method [4].

2.3 Thermophysical Properties

Three different materials are used to build the louver for solar energy harvest and storage. The physical properties of water are functions of temperature as given in COMSOL Multiphysics software. The dynamic viscosity of water with varying temperature in the range from 273.15K to 413.15K is

$$\mu_w = 1.38 - 0.02122\mathrm{T} + 1.36 \cdot 10^{-4}T^2 - 4.645 \cdot 10^{-7}T^3 + 8.904 \cdot 10^{-10}T^4 - 9.08 \cdot 10^{-13}T^5 + 3.8457 \cdot 10^{-16}T^6 \tag{4}$$

The heat capacity of water in a temperature range from 273.15K to 553.75K is

$$C_{pw} = 12010.1471 - 80.4T + 0.31T^2 - 5.382 \cdot 10^{-4}T^3 + 3.62536 \cdot 10^{-7}T^4 \tag{5}$$

The density of water varies with temperature as

$$\rho_w = 838.466 + 1.4\mathrm{T} - 0.003 \cdot T^2 + 3.718 \cdot 10^{-7}T^3 \tag{6}$$

The thermal conductivity of water is

$$k_w = -0.869 + 0.0089488T - 1.58366345 \cdot 10^{-5}T^2 + 7.97543259 \cdot 10^{-9}T^3 \tag{7}$$

The temperature dependence of copper and glass in a small temperature range is usually weak. In this study, the thermal physical properties of both copper tubes and glass layers are assumed to be constant with values adopted at 30 ℃. For the copper, the heat capacity is 385 J/(kgK), density 8960 kg/m^3, and thermal conductivity 400 W/(mK). For the silica glass, the heat capacity is 705 J/(kgK), density 2203 kg/m^3, and thermal conductivity 1.38 W/(mK).

2.4 Boundary conditions

Conjugate heat transfer is considered in the glass and water regimes. Therefore, it is not needed to specify the boundary conditions between the water and glass interface. The ambient air surrounding the glass louver and copper tubes is set at 293.15K. Natural convection exists at the out surfaces of the glass layers and copper tubes.

For the external surfaces of the vertical and inclined glass plates, the following correlation [11] of natural convection is adopted:

$$h = \begin{cases} \frac{k}{Lc}\left(0.68 + \frac{0.67(\cos(\emptyset)Ra_{Lc})^{1/4}}{\left(1+\left(\frac{0.492k}{\mu C_p}\right)^{9/16}\right)^{4/9}}\right) & \text{if } Ra_{Lc} \le 10^9 \\ \frac{k}{Lc}\left(0.825 + \frac{0.378Ra_{Lc}^{1/6}}{\left(1+\left(\frac{0.492k}{\mu C_p}\right)^{9/16}\right)^{8/27}}\right)^2 & \text{if } Ra_{Lc} \ge 10^9 \end{cases} \tag{9}$$

in which,

$$Ra_{Lc} = \frac{g\beta|T_s - T_\infty|Lc^3}{\upsilon\alpha} \tag{10}$$

For surfaces 1-3 shown in Fig. 1, Lc = W, and for surfaces 4 and 5, Lc = 0.5W. $\emptyset$ is the tilt angle of the glass plates and $\emptyset = 0$ for the vertical plates. The tilt angle of the two inclined glass plates is $-60°$ and $60°$, respectively. All material properties are evaluated at $(T_s - T_\infty)/2$. The correlations are valid for $10^4 \le Ra_{Lc} \le 10^{13}$.

For the horizontal copper tubes, the following correlation [11] is validated for $Ra_D \le 10^{12}$

$$h = \frac{K}{D}\left(0.6 + \frac{0.387Ra_D^{1/6}}{\left(1+\left(\frac{0.559}{Pr}\right)^{9/16}\right)^{8/27}}\right)^2 \tag{11}$$

The inlet water temperature from the entry tube is assumed to be 298.15K. Uniform velocity distribution at the inlet is assumed.

$$u = u_i,\ T = T_i \tag{12}$$

For the outlet flow, we have extended a section of imaginary well-insulated copper tube such that fully developed flow and adiabatic flow can be assumed, i.e.,

$$\frac{dT}{dX} = 0 \text{ and } \frac{du}{dx} = 0 \tag{13}$$

2.5 Meshes and simulation time

The louver was meshed into 17,432, 65,568, 169,867 and 895,501 elements, respectively. Satisfactory results could be obtained with the mesh number of 169,867 and this mesh is applied below. The computational CPU time is about 8 min 54 sec in a laptop with Intel(R) core(TM) i7-4790K CPU at 4.00GHZ, 4 cores.

3. RESULTS AND DISCUSSION

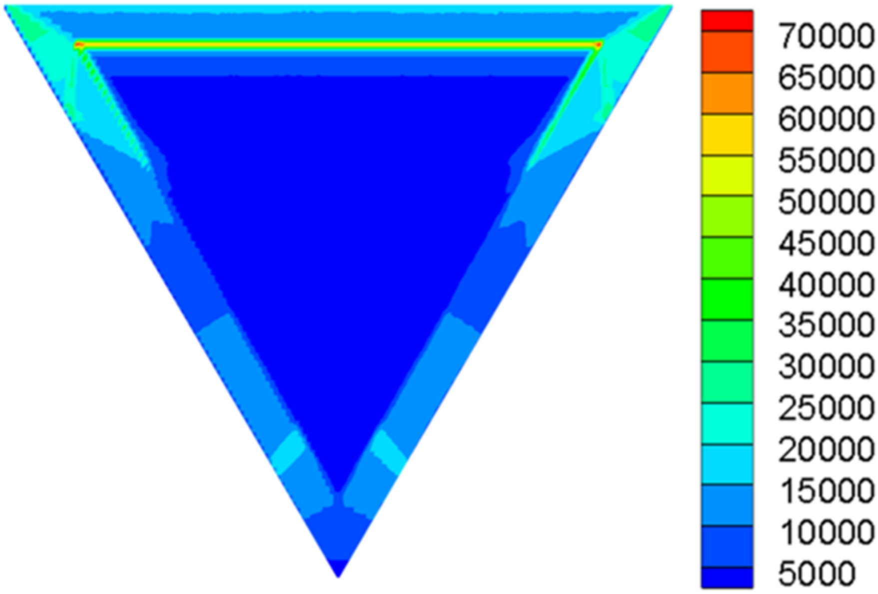

Fig. 3 Distribution of heat source due to absorption of collimated sunlight (W/m^3)

The solar incidence on the louver surface is assumed collimated sunlight of $E = 500W/m^2$. The distribution of the solar energy deposition in the cross-section of louver is shown in Fig. 3, which was calculated by Cai et al. [10]. The total absorption efficiency η is 55.5%. The overall absorbed solar energy in the louver is calculated as

$$\Delta E_{abs} = E\eta(L - 2\tau)W \tag{14}$$

For the current case, ΔE_{abs}= 20.94W. This is the maximum solar energy absorbed by a single louver. It will result in a temperature rise in the water flow. Part of the thermal energy will be dissipated to the ambient due to natural convection surrounding the louver.

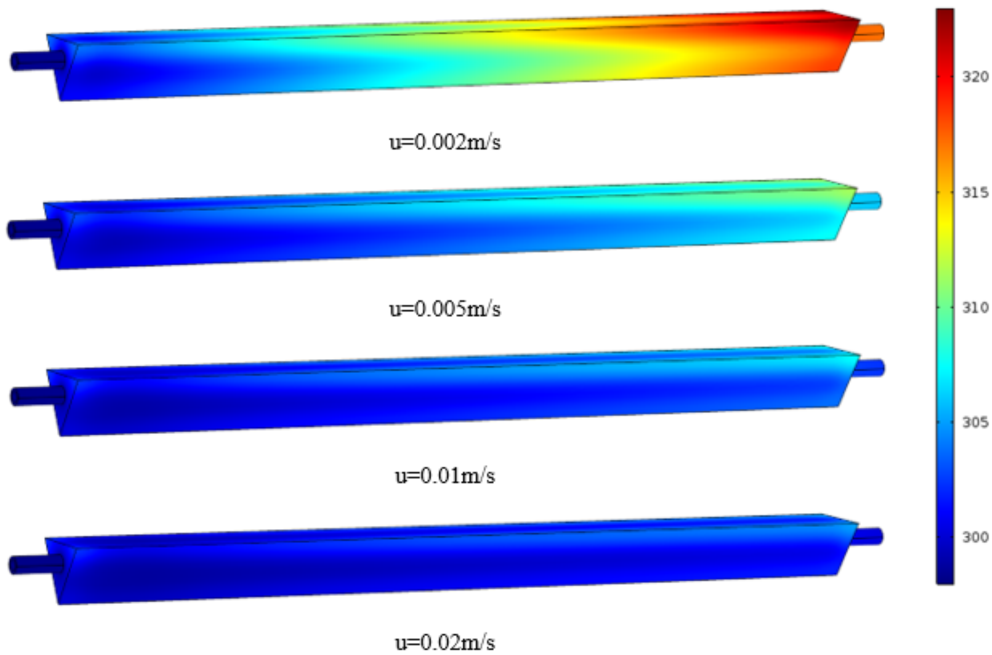

Fig. 4 3D temperature contours for four different flow velocities.

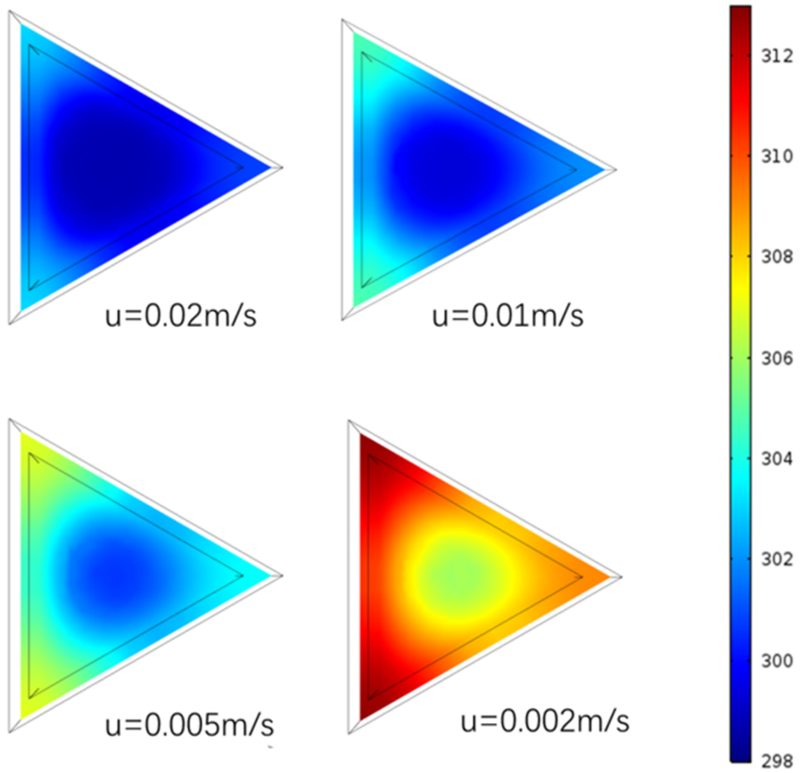

Fig. 5 2D cross-sectional temperature distributions at the middle of the glass louver.

3.1 Temperature rise

Fig. 4 shows the 3D temperature contours of the glass louver at four typical flow velocities. When fluid velocity is 0.002m/s, there is an obvious temperature rise for the glass louver, from 298.15K at the inlet to 317.09 K at the outlet. From Fig. 5, it is seen that the temperature is higher near the solar irradiation incident surface than other area inside the louver. This is because more solar energy is absorbed in the glass layer facing the solar irradiation. In general, the temperatures in the three glass layers are higher than the temperature in the water region. Of course, this is for the case of a single louver. Under a cascade system of many louvers in series, the water temperature keeps rising flowing through louvers, and the louver glass temperature will not be lower than the final output water temperature of a cascade system. Figures 4 and 5 also show that, with increasing flow velocity to 0.005m/s, 0.01m/s and 0.02m/s, the temperature rise in each single louver drops.

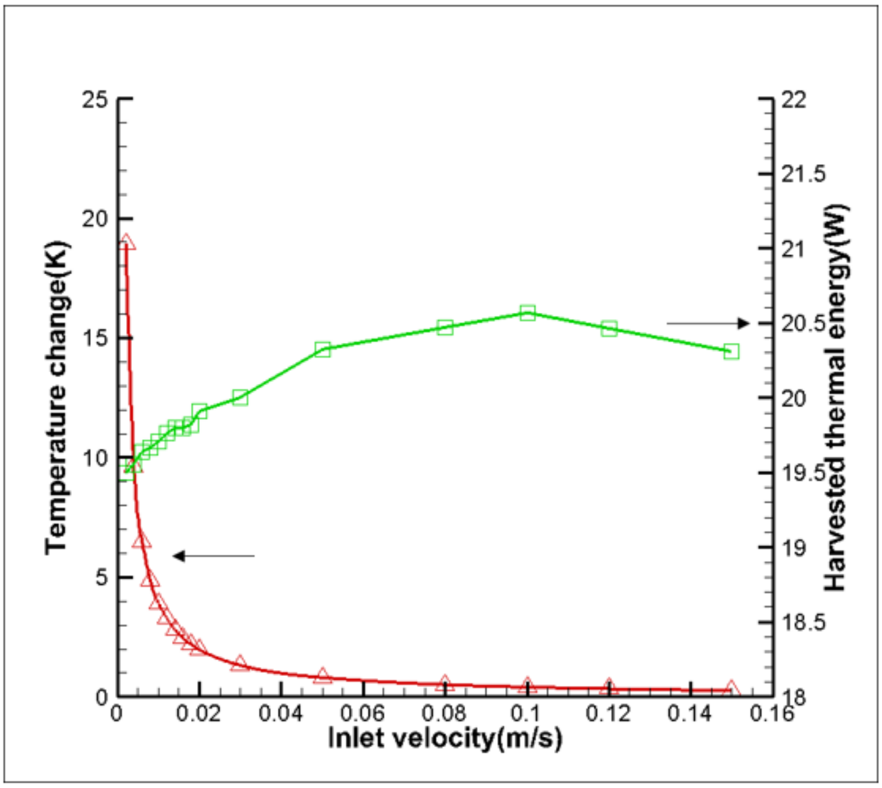

Fig. 6 Temperature rise and harvested thermal energy vs. velocity

Fig. 6 plots the temperature rise and the harvested thermal energy from the water inlet to the outlet (two ends of the tubes) in a single louver verses flow velocity change from 0.002m/s to 0.15m/s. The thermal energy increase is calculated by

$$\Delta Q = \dot{m}(C_{p,out}T_{out} - C_{p,in}T_{in}) \tag{15}$$

In which, ΔQ is the harvest thermal energy for the glass louver, $\dot{m}$ is the mass flowrate of water, and T_{in} and T_{out} refer to the inlet and averaged outlet temperature, respectively. The difference of these two temperatures is the temperature rise. It is seen that, though the temperature rise drops with increasing flow velocity, the harvested thermal energy increases initially and then drops after reaching about 0.1 m/s.

3.2 Velocity distribution

The inlet flow velocity varies from 0.002m/s to 0.15m/s. When the velocity is 0.15m/s, Reynold number is 1905. Thus, the flow under consideration is always laminar.

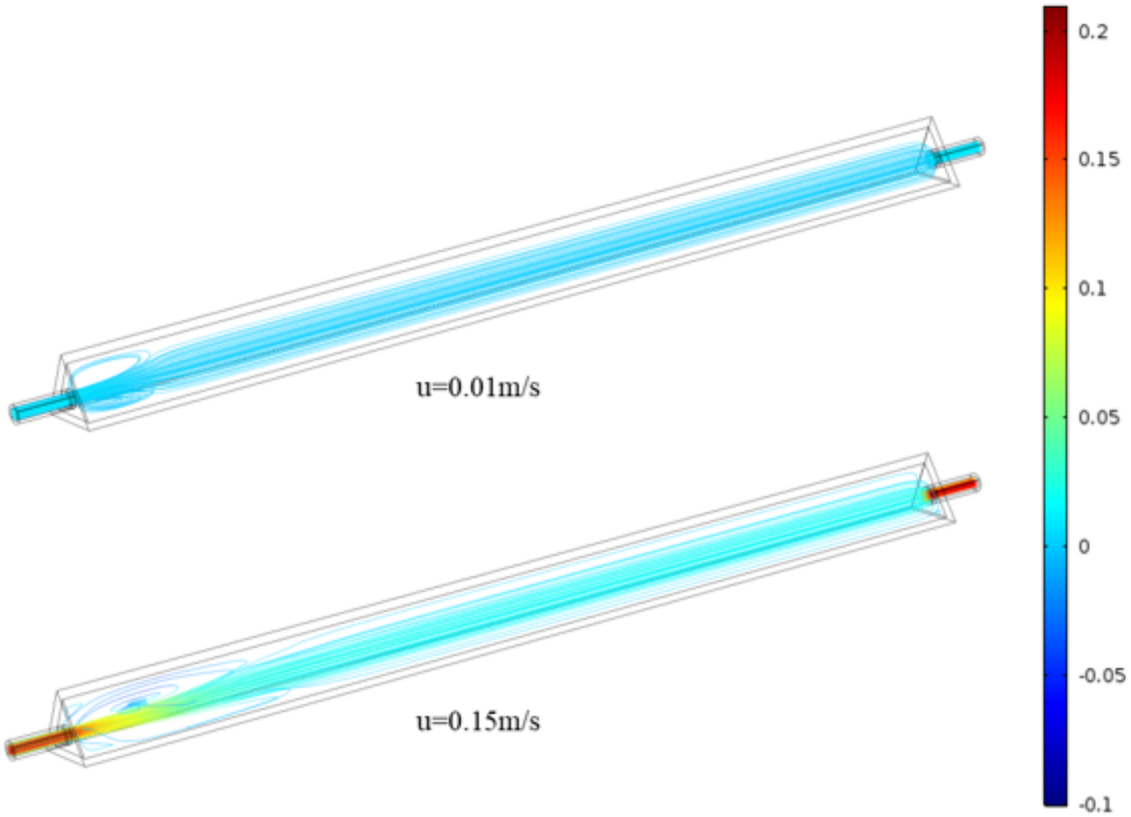

Fig. 7 the streamline of velocity field inside glass louver

Figure 7 shows the distribution of streamlines for two typical velocities. There is a backflow around the junction of copper tube and prism glass louver, for the area of section increases suddenly.

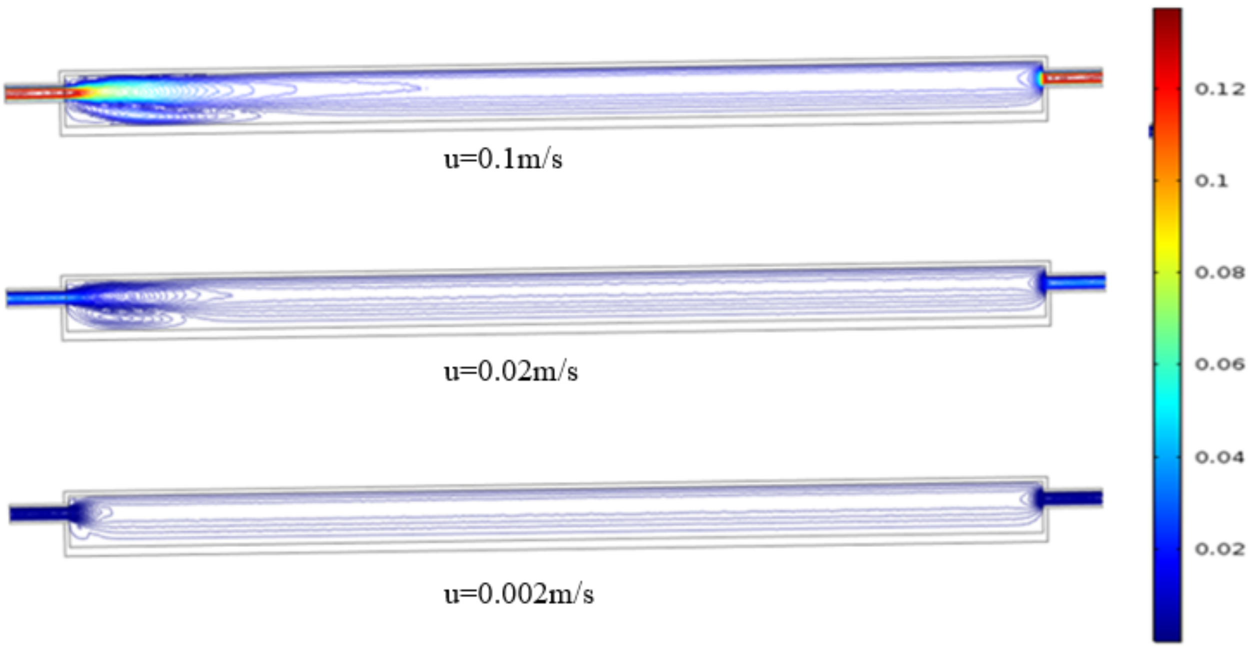

Fig . 8 Velocity contours for three different velocities.

Figure 8 plots the velocity contours inside the glass louver for three different velocities. It is seen that the backflow area around the junction of copper tube and prism glass louver enlargens as the velocity increases.

3.3 Pressure difference

Fig. 9 shows the pressure drop between two tube ends in a single louver and the pumping power required to maintain the flow. The power for driving the water flow is related to the pressure difference as follows:

$$PW = \Delta P\dot{V} \tag{16}$$

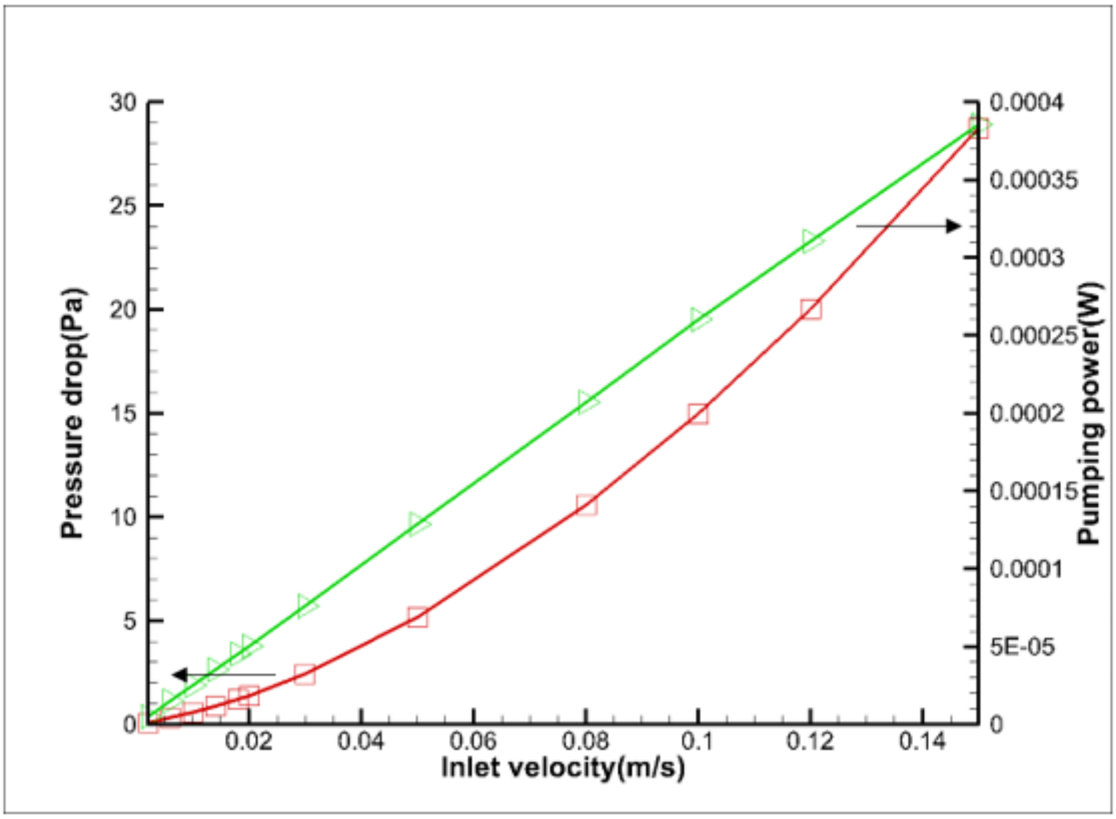

Fig. 9 Pressure difference and pumping power vs. inlet velocity.

Fig. 9 indicates that the pressure drop raises with the increase of inlet velocity. At the maximum velocity of 0.15 m/s, the pressure drop is about 29 Pa, and the pumping power is about 0.38 mW, which is negligible as compared to the solar thermal energy harvested (20.3 W) showing in Fig. 6.

4. CONCLUSION

The paper investigated water flow and heat transfer in a water-filled glass louver under the irradiation of collimated sunlight. With the variation of inlet velocity, the temperature rise and pressure drop are calculated. Some conclusions can be drafted as follows:

1. The total energy harvested and the outlet averaged temperature are affected by the inlet velocity, i.e., the flowrate. When the flow velocity increases, the outlet temperature decreases. The harvested thermal energy is the largest around an inlet velocity at 0.1 m/s. A single louver could harvest about 19.5 to 20.5 W solar energy under the present irradiation condition. A cascade louver system for a typical window could be consisted of 20-30 louvers, i.e., the louver device in behind a window could harvest 100-150 W solar energy.

2. When the inlet velocity increases, the pressure drop increases. However, the pumping power consumed is negligible as compared to the solar thermal energy harvested.

ACKOWLEDGMENT

This material is based upon work supported by the National Science Foundation under grant No. ECCS-1505706. Yi Nan acknowledges fellowship support from the China Scholarship Council (CSC) for study at Rutgers University.

NOMENCLATURE

L	length of triangular glass louver (m)		L1	length of inner glass louver	(m)
τ	thickness of glass louver	(m)	H	height of glass louver	(m)
ρ_w	density of water	(kg/m^3)	u	velocity of inlet	(m/s)
P	pressure of water inside glass louver (pa)		g	acceleration of gravity	(m/s^2)
C_{pw}	heat capacity of water	(J/(kg·K))	k_w	thermal conductivity of water	(W/(m·k))
T	temperature of water inside glass louver (K)		T_∞	temperature of environment	(K)
T_s	temperature of surface of glass louver(K)		T_0	temerpature of water at inlet	(K)
ΔQ	harvest thermal energy	(W)	$\dot{V}$	volume flow rate	(m^3/s)
D	diameter of inlet and oulet tube	(m)	D1	diameter of inlet and oulet inner tube	(m)
β	thermal expansion coefficient	(1/K)	υ	kinematic viscosity	(m^2/s)
α	thermal diffusivity	(m^2/s)	$C_{p,in}$	heat capacity of water at inlet	(J/(kg·K))
$C_{p,out}$	heat capacity of water at outlet	(J/(kg·K))	T_{in}	temperature of water at inlet	(K)
T_{out}	temperature of water at outlet	(K)	η	absorption coefficient	

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