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RESEARCH ARTICLE

NUMERICAL ANALYSIS OF FLOW IN PARALLEL-CONNECTION OF SOLAR HEAT EXCHANGER

[1,*]Namory Camara and [2]Lu Huilin

[1] Department of Physics, Faculty of Science and Techniques, E3206, Bamako, Mali
[2] Department of Power Engineering, Harbin Institute of Technology, Harbin, 150001, China

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ABSTRACT

Flow and temperature distribution in parallel-connection of solar heat exchanger are numerically analyzed. Fluent software is used to solve governing differential equations with boundary conditions. Numerical results indicate that it is important to take the flow maldistribution into account for a better design of the parallel-connection of solar heat exchanger. It is also found that the heat transfer rate of the optimized model is increased by 6.0% compared to that of the base type.

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INTRODUCTION

The continuing depletion of fossil fuels and the environmental hazards posed by the needs of future development are gradually shifting the path of development towards sustainability, better sociability, and environmental responsibility, which in turn emphasizes the need for renewable energy sources. The heat capacity of a parallel-connection solar heat exchanger (PCSHE) is about 150–200% larger than that of the conventional heat exchanger. The high heat capacity of the PCSHE can meet the requirements of compactness and lightness. The PCSHE has a good thermal performance, but it is different in structure compared with conventional heat exchangers. Therefore, the study on the internal heat and flow characteristics is required. The uniform flow distribution is the most important phenomenon when the heat and flow characteristics of multiple passages are considered. Nakamura *et al.* (1989) designed passages of a power transformer using the multi-block method so that the flow distribution of the air in each passage can be uniform. Karvounis and Assanis (1993) examined the flow distribution inside a catalytic converter by varying the size of its inlet, based on the fact that the more uniform the distribution of inlet velocity, the more uniform the flow rate in each passage. The PCSHE is widely used in power and process industries. Initially, it was designed for the dairy, brewery and food processing industries where cleaning and maintenance is of prime importance. Later, it was found that the PCSHE has many advantages, like high heat transfer coefficient, compactness, flexibility, and less fouling etc. This type of heat exchanger is also used in power and chemical process industries today. Initially, modeling thermal performance of PCSHE was carried out, based on the assumption of equal flow rate in all the channels (Watson *et al.,* 1960; Buonopane *et al.,* 1963), which is an ideal case of no flow maldistribution. In the area of flow distribution in manifold systems, the analytical model developed by Bajura (1971) explained about the flow distribution inside the different manifold design having different area ratios and flow resistances. In the recent past, the literature shows many numerical and analytical studies to find out the flow distribution along the inlet and outlet ports. This is useful to predict the flow behavior of the exchanger. Effect of unequal flow distribution in parallel and reverse flow manifold systems was analyzed by Datta and Majumdar (1980), and expressed the distribution in the channels in the form of closed form equation using the general flow channeling and unification concept by Bajura and Jones (1976). The thermal performance was shown by an analytical study made by Rao *et al*. (2002). In this study, the numerical analysis on the thermal performance of a PCSHE is performed. To evaluate the thermal performance, flow uniformity is defined. The design parameters are selected and the effects of these parameters on heat and flow characteristics are examined.

Corresponding author: **Namory Camara,**
Department of physics, Faculty of Science and Techniques, E3206, Bamako, Mali.

Theoretical model

The parallel-connection solar heat exchanger and coordinate system is illustrated in Fig 1. The energy conservation equations to describe fluid flow and heat transfer are given below. Energy equation by conductivity at unsteady state through parallel-connection walls is:

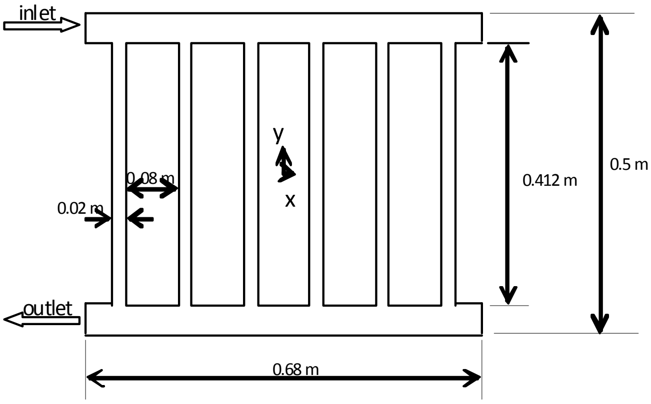

Fig. 1. Parallel connection and coordinate system

$$\frac{\partial}{\partial t}(\rho_s C_s T_s) + \nabla \cdot (k_s T_s) = 0 \qquad \text{....................... (1)}$$

Where ρ_s, k_s and C_s are respectively density, thermal conductivity and heat capacity of steel materials, and T_s is wall temperature. Water flow in the pipes, and its temperature is increased, and velocity varied in radial and axial directions. Hence, flow behavior of water in the parallel-connection must be satisfied the momentum and energy conservations. The mass conservation of water inside pipes is

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \qquad \text{...................................... (2)}$$

where ρ and u are fluid density and velocity. The momentum equation of water is

$$\frac{\partial}{\partial t}(\rho u) + \nabla \cdot (\rho u u) = \nabla P + \nabla \cdot [\mu(\nabla u + \nabla u^T)] \qquad \text{...... (3)}$$

where P is fluid pressure, and μ is fluid viscosity. If flow is laminar flow, the fluid viscosity can be obtained from molecular-type viscosity, while the value is determined from eddy-viscosity model for turbulent flow. The energy conservation of water is expressed as follows:

$$\frac{\partial}{\partial t}(\rho C_w T) + \nabla \cdot (\rho u C_w T) = \nabla \cdot [\frac{\mu}{\Pr}\nabla(C_w T)] \qquad \text{....... (4)}$$

where T, C_w and Pr are respectively temperature, heat capacity and Prandtl number of water. In the initial condition, the pipes were assumed empty, and water velocity zero. The temperature of the wall is set to ambient temperature. At t>0, at the inlet water mass flux and flux incident are given.

At the wall, the no-slip boundary used for water flow.

Model and numerical procedures

Equations (1) to (4) are numerically solved. A set of differential equations has been developed to simulate dynamic behavior and steady-state performance of parallel connection of solar heat exchanger. The fluid velocity is obtained to solve momentum equation of the fluid. The temperature of wall and fluid are determined from energy equation. The governing equations are discretized by the finite volume method, and the power-law scheme is used to discretize the convection-diffusion terms. The parameters used are given Table 1.

Simulation results and discussions

Fig 2 shows the velocity components of fluid along the pipe diameter for six pipes for a displacement y=0.069 m from the center of parallel-connection. It can be seen that the pipes exhibit a common characteristic of velocity distribution with increasing diameter. The velocity seems to increase gradually as the pipe diameter increases from zero. The velocity peaks at a diameter D_p, the corresponding velocity can be designated V_p. The velocity then drops off gradually again after this peak. For some pipes, there are two peaking diameters D_{p1} and D_{p2} with corresponding velocities V_{p1} and V_{p2} while for some others the two peaking diameters seem to merge into one D_p and the peak velocities merge into V_p. Different pipes have different values for D_p and V_p. For pipes 1, 3 and 4, it can be seen that they have a D_{p1} of 0.00154 m, 0.00222 m, and 0.002 m respectively. They also have a D_{p2} of 0.01692 m, 0.01556 m and 0.0018 m in the same order. However for pipes 2, 5 and 6 they only have one peak diameter D_p at 0.016 m, 0.01636 m, and 0.01714 m respectively. Pipes 1, 3 and 4 have a crest velocity V_c after the first peak velocity V_{p1}, the crest velocity occurs at a corresponding diameter D_c from where the velocity component rises again to the peak value V_{p2}. The D_c values for pipes 1, 3 and 4 are 0.00769 m, 0.00444 m, and 0.006 m respectively. The velocity of fluid is zero at the walls because the no slip boundary condition was used. Fig 3, presents the velocity components of fluid along the pipe diameter for six pipes at middle section of parallel-connection with no displacement. Just like it was observed in Fig 1, some pipes have two peaking diameters D_{p1} and D_{p2} with corresponding

Table 1. Parameters of the parallel-connection, steel material and water

Width of parallel-connection (m)	0.68	water inlet pressure, p_{fi} (Pa)	100600
Height of parallel-connection (m)	0.5	water specific heat, C_w (J/kg.K)	4180
Pipe diameter (m)	0.02	steel density, $\rho_s\,(kg/m^3)$	8030
Height of pipe (m)	0.412	steel thermal conductivity, $k_s\,(w/m.K)$	16.27
Ambient temperature, T_∞ (k)	300	steel specific heat, C_s (J/kg.K)	502.48
Flux incident (w/m^2)	1000		

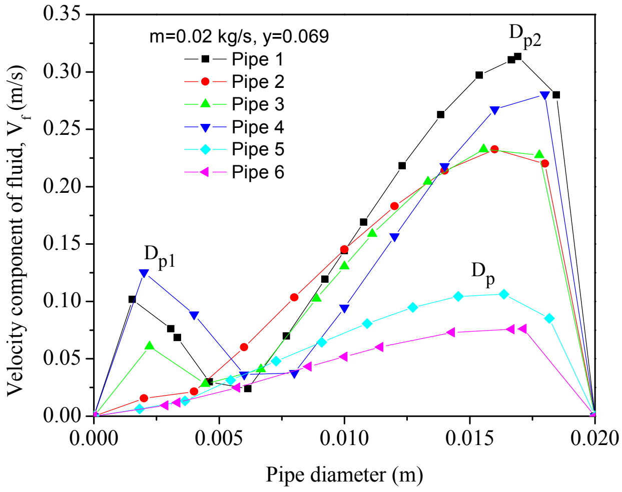

Fig. 2. Profile of velocity components of fluid at y= 0.069 m from the center

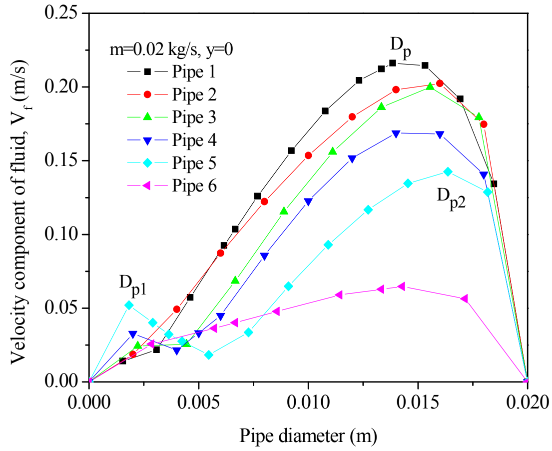

Fig. 3. Profile of velocity components of fluid at middle section

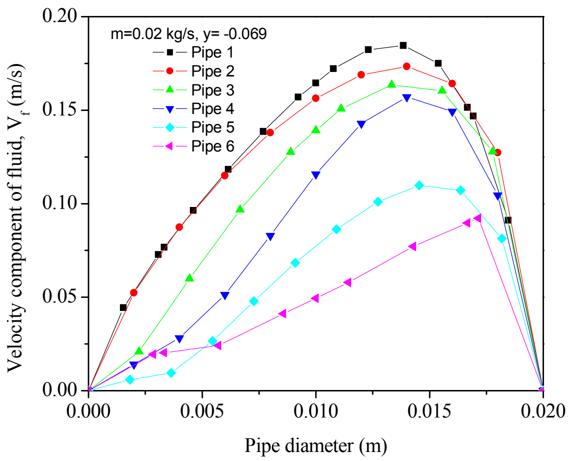

Fig. 4. Profile of velocity components of fluid at y= -0.069 m from the center

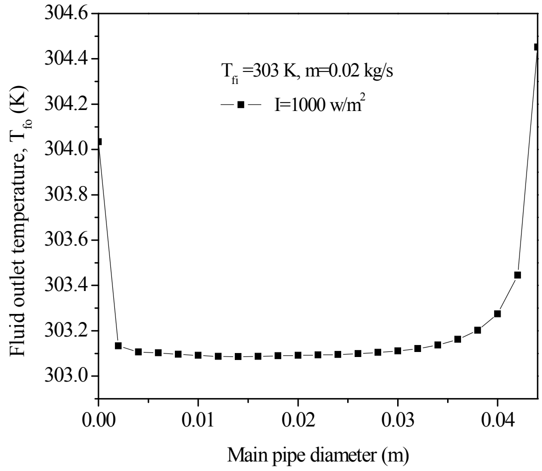

Fig. 5. Distribution of fluid outlet temperature of main tube diameter

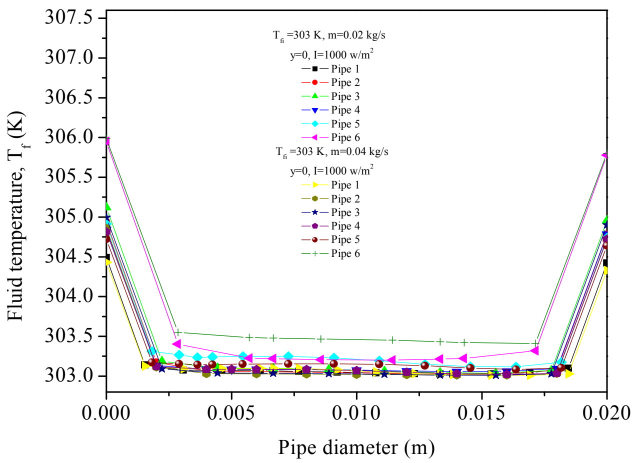

Fig. 6. Effect of mass flux on temperature of fluid

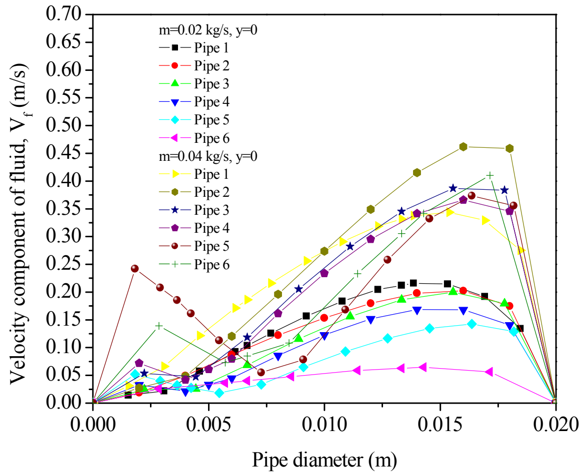

Fig. 7. Effect of mass flux on the velocity component of fluid

velocities V_{p1} and V_{p2} while for others the two peaking diameters seem to merge into one D_p and the peak velocities merge into V_p with different pipes have different values for D_p and V_p. However there is a reversal of the velocity distribution by tube position. For pipes 1, 2, 3 and 6 there is only one peak diameter D_p at 0.01385 m, 0.016 m, 0.01556 m, and 0.01429 m respectively.

Only pipes 4 and 5 have two peak diameters (and peak velocity components) and a crest value for each of the two quantities. These occur for pipe 4 at D_{p1}, D_{p2} and D_c equal to 0.002 m, 0.014 m and 0.004 m respectively. For pipe 5 the values are 0.00182 m, 0.01636 m and 0.00545 m in the same order. Additionally it is observed that the maximum peak velocity for all the tubes is lower at the centre than at a point away towards the inlet. Fig 4 gives the velocity components of fluid along the pipe diameter for the six pipes with a displacement of y = -0.069 m from the center of parallel-connection. Unlike in the previous observations, here all the pipes now exhibit only one peaking diameter D_p. The velocity components rise gradually as we move from the tube center, peaking at the value D_p for each pipe and then dropping off as the tube wall is approached where the velocity is zero in accordance to the assumed boundary condition. In serial order the tubes peaking diameters D_p are 0.01385 m, 0.014 m, 0.01333 m, 0.014 m, 0.01455 m and 0.01714 m respectively. It is also observed that the maximum peak velocity is also lower than that at the centre of the parallel-connection. Distribution of fluid outlet temperature of main pipe diameter is illustrated in Fig 5. Fluid outlet temperature is high at the walls and low inside tube diameter. The flow distribution show that the fluid outlet temperature decreases between 0.000 m and 0.012 m, constant between 0.012 m and 0.02 m, and increases between 0.02 m and 0.044 m. Fig 6 shows the effect of mass flux on temperature of fluid. The temperature of fluid decreases with the increase of mass flux. It is high at the walls and low at the center of pipe diameter. Fig 7 gives the effect of mass flux on the velocity component of fluid. The fluid velocity increases with the increase of mass flux. It is zero at the walls and increases inside the pipe diameter.

Conclusion

The performance of two-dimensional parallel connection was numerically investigated. For better design of the parallel-connection of solar heat exchanger, it is important to take the flow maldistribution into account. It is influenced by design parameters, operational parameters, and meteorological parameters. Others are environmental parameters and the mass flow rate.

Nomenclature

C_f Fluid heat capacity rate, $C_f = mC_p$, W/K

C_p Fluid specific heat, J/kg K

T_{fi} Fluid inlet temperature, K

T_f Fluid temperature, K

T_{fo} Fluid outlet temperature, K

T_∞ Ambient temperature, K

V_f Velocity component of fluid, m/s

p_{fi} Fluid inlet pressure, Pa

m Mass flow rate, kg/s

x, y Coordinates

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