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CFD Based Analysis of Flow Distribution in a Coaxial Vacuum Tube Solar Collector with Laminar Flow Conditions

[1]Raja Mishra, [2]Dr. K V Modi

[1]Research scholar (Energy Engineering)
[1, 2] Department of Mechanical Engineering, Govt. Engineering Collage, Valsad (GUJ), India

Abstract: **A computational fluid dynamics (CFD) analysis has been conducted to find the pressure losses for dividing and combining fluid flow through a tee junction of a solar collector manifold. Simulations are performed for a range of flow ratios and Reynolds numbers, and equations are developed for pressure loss coefficients at junctions. A theoretical model based on successive approximations then is employed to estimate the isothermal and non-isothermal flow distribution in laminar range through a collector consisting of 60 vacuum tubes connected in parallel in a reverse (U-configuration) and parallel (Z-configuration) flow arrangement. The results are in reasonable agreement with the available experimental results for U-configuration. The proposed CFD based strategy can be used as a substitute to setting up and performing costly experiments for estimating junction losses.**

Keywords: **computational fluid dynamics, junction pressure loss coefficient, dividing manifold, combining manifold, flow distribution.**

1. BACKGROUND

In a typical vacuum tube solar collector design, the fluid flow usually is divided in a manifold to risers connected in parallel. After extracting heat from the attached absorber, the fluid passages are combined in a manifold and the hot fluid is led to the user. Heat gain of a solar collector is affected by the flow rate through the individual risers, and uniform distribution is desirable to achieve the same thermal output from all the tubes for best performance, which is not the case in reality. Both the collector's overall flow rate and flow nonunifor-mity affect the collector efficiency.

The risers are generally connected at right angles to the manifold, thus forming a tee joint at each connection which leads to local disturbances. A varying local pres-sure drop for a flow through such a manifold results in an uneven flow distribution through the whole collector. Wang and Yu [5] developed a numerical model to calculate the isothermal flow distribution using mass and momentum equations at each branch of the header system. Wang and Wu proposed a discrete numerical model

And demonstrated the flow and temperature distribution in a flat-plate solar collector for U- and Z-configurations by taking into account the effects of buoyancy and longitudinal heat conduction Jones and Lior developed a discrete hydrodynamic model, and the resulting non-linear algebraic equations were solved numerically. For negligible buoyancy effects, they investigated the effects of geometrical parameters of the collector such as the ratio of riser to manifold diameter, number of risers, and length of risers on the flow no uniformity. Carried out CFD calculations to estimate the flow and temperature distribution in a flat-plate solar collector consisting of 16 risers connected in U-configuration, having a tilt of 40° The influences of flow rate, fluid properties, collector tilt, and collector inlet fluid temperature were investigated. Later, for the same collector, Fan and Furbo studied the buoyancy effects on fluid and temperature distribution by means of CFD calculations. They found that at a certain low flow rate, buoyancy effects are of the same order as the pressure drop in the risers or even larger, which results in a more no uniform flow distribution. The pattern of flow distribution reverses as compared to the case of high flow rate (25 l/min) with negligible buoyancy effects.

Glembin experimentally investigated the flow distribution in a horizontally placed coaxial vacuum tube solar collector consisting of 60 parallel vacuum tubes connected in U-configuration. They adopted a procedure where flow distribution was calculated from the measured tube outlet temperatures for a range of inlet temperatures and mass flow rates.

An alternative way for the determination of flow distribution is to solve it as a piping network where flow is divided amongst the parallel piping, and each flow path leads to the same pressure loss. The riser components connected to the manifolds interrupt the smooth flow of the fluid in the manifolds and cause additional losses. One of the key parameters in evaluating the flow distribution through such a piping network is the pressure loss at the junctions of dividing and combining manifold. At the junctions, the pressure loss coefficient, in general, depends on the geometry of the component and the Reynolds number, just like the friction factor. However, when the Reynolds numbers are very large, it is usually assumed to be independent of the Reynolds number. Based on the experimental data for turbulent flow, these junction loss coefficients can be found in the literature in the form of analytical or empirical expressions characterized by branch angle, area ratio, and flow ratio, which are not appropriate to use for laminar flow conditions. On the other hand, Weitbrecht performed experiments on a collector with 10 risers connected in

Z-configuration and used the experimentally obtained junction loss coefficients to determine the flow distribution analytically with laminar flow conditions, which form the basis for this paper.

The aim of this work is to demonstrate the alternate use of CFD simulations instead of experiments to estimate the pressure loss coefficients at the junctions for a range of locally changing flow ratios and Reynolds numbers, and using those to calculate the flow distribution theoretically. A theoretical approach as adopted by Weitbrecht is used to estimate the isothermal flow distribution in the horizontally placed collector for both U and Z-configurations. Temperature effects on fluid properties are also taken into account for non-isothermal flow distribution, but the buoyancy effects are neglected for a horizontally placed collector. Modeling results then are compared and validated with those predicted experimentally by Glembin. Moreover, the influence of various other parameters is also investigated.

2. METHODS

Collector specification:

The collector considered in this study consists of two modules having a total number of 60 vacuum tubes connected in parallel in U-configuration and placed horizontally as shown in Figure 1a. Each vacuum tube contains a flat absorber sheet of 0.1 m^2 area coated with

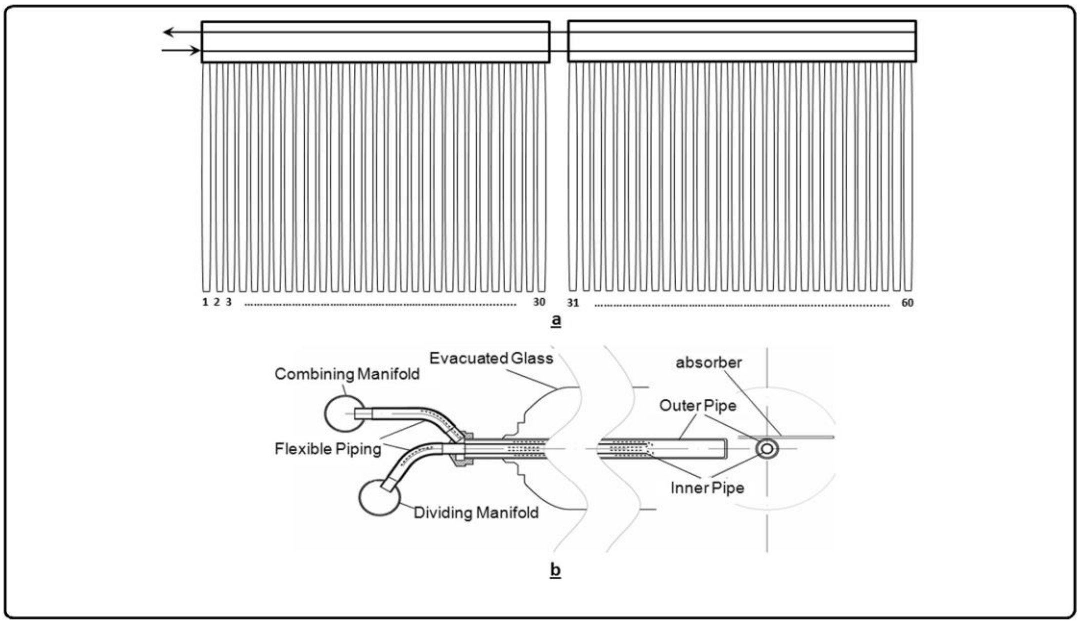

Figure 1: Schematic of the solar collector. (a) Collector group of 60 vacuum tubes (b) vacuum tube connected to manifold

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A selective surface (TiNOX) on a copper substrate and welded to the coaxial copper piping for fluid flow (Figure 1b. A small part of the riser is intruded in-side the manifolds, and flexible piping elements are used to connect the coaxial piping to the dividing and combining manifolds as illustrated in Figure 1b.

Table 1 summarizes the geometrical parameters of the collector. A mixture of water and propylene glycol is used as a working fluid.

Junction pressure loss coefficients:

The main focus of the study is to determine the pressure loss coefficients at the junctions. A part of the manifold attached to the riser forming a tee joint is taken into consideration for the analysis, and the actual flexible corrugated piping elements at inlet and outlet manifolds (Figure 1b) are assumed as straight pipe, as shown in Figure 2. The effect of adjacent branches on each other is not considered.

The loss coefficient k represents the energy dissipation at the junction and is defined as follows:

$$k = \frac{\Delta p}{\rho V_c^2/2},$$

Where p is the pressure drop between the upstream and downstream sections of the junction between which the pressure loss under consideration occurs. Therefore, two loss coefficients are defined to characterize a junction loss: one for straight flow (with the index st) and one for side flow (with the index s). In any case, the velocity V_c is the one in the combined flow (see Figure 2).

Based on the idea of Weitbrecht, the following relation is used to determine the loss coefficient at the junction:

$$k = \frac{\Delta p_{i-j} - \Delta p_{f,i}}{\rho V_c^2/2},$$

Table 1: Material and geometrical parameters of the solar collector

Description	Specification
Outside diameter of outer riser pipe (mm)	12
Inside diameter of outer riser pipe (mm)	10.4
Length of outer riser pipe (mm)	1,820
Outside diameter of inner riser pipe (mm)	6
Inside diameter of inner riser pipe (mm)	5.3
Length of inner riser pipe (mm)	1,750
Inside diameter of dividing/combining	22
manifold pipe (mm)	
Spacing between risers (mm)	70
Length of riser intruded inside the manifold	5
pipe (mm)	

Occur due to friction only because of the flow from inlet to outlet of the model. It is calculated by standard pressure drop relations. According to Equation 2, equations can be written to represent all the loss coefficients with reference to Figure 2:

$$k_{\mathrm{div,st}} = \frac{\Delta p_{c-\mathrm{st}} - (\Delta p_{f,c} + \Delta p_{f,\mathrm{st}})}{\rho V_c^2/2} \quad (3)$$

$$k_{\mathrm{div},s} = \frac{\Delta p_{c-s} - (\Delta p_{f,c} + \Delta p_{f,s})}{\rho V_c^2/2} \quad (4)$$

$$k_{\mathrm{com,st}} = \frac{\Delta p_{\mathrm{st}-c} - (\Delta p_{f,\mathrm{st}} + \Delta p_{f,c})}{\rho V_c^2/2} \quad (5)$$

$$k_{\mathrm{com},s} = \frac{\Delta p_{s-c} - (\Delta p_{f,s} + \Delta p_{f,c})}{\rho V_c^2/2} \quad (6)$$

while

$$\Delta p_{c-\mathrm{st}} = p_c - p_{\mathrm{st}} \quad (7a)$$

$$\Delta p_{c-s} = p_c - p_s \quad (7b)$$

$$\Delta p_{\mathrm{st}-c} = p_{\mathrm{st}} - p_c \quad (7c)$$

$$\Delta p_{s-c} = p_s - p_c \quad (7d)$$

$$\Delta p_{f,i} = f\frac{L_i}{D_i}\frac{\rho V_i^2}{2}(i = c, s, \mathrm{st}) \quad (8)$$

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where $L_c = L_{st}$, as shown in Figure 2; values of Δp_{c-st}, Δp_{c-s}, Δp_{st-c}, and Δp_{st-c} are calculated from CFD simulations. The friction factor f can be calculated as follows:

$$f = \frac{64}{Re} \quad For\, \mathrm{Re} < 2,300, \tag{9a}$$

$$\frac{1}{\sqrt{f}} = -1.8 \ \log\left[\frac{6.9}{\mathrm{Re}} + \left(\frac{\epsilon/D}{3.4}\right)^{1.11}\right] \quad \text{For Re} > 2{,}300. \tag{9b}$$

CFD analysis:

A 3D meshed model of a manifold connected to a riser is built in GAMBIT (Fluent Inc., Lebanon, NH, USA)

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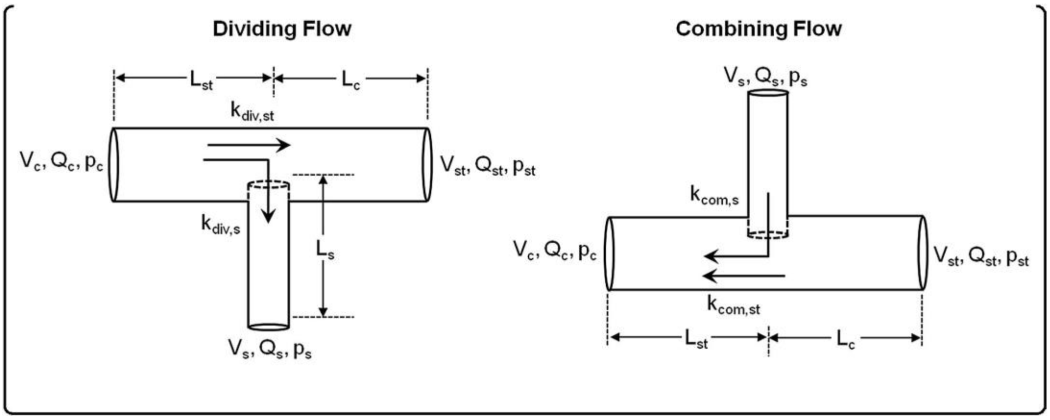

Figure 2: Loss coefficients at the dividing and combining manifold.

In order to get the structured mesh, the junction portion of the model is divided into three parts, and each part is meshed separately, as shown in Figure 3a. Initially, part 2 is meshed, then parts 1 and 3 are meshed, and at the end, the remaining straight parts of the manifold are meshed. Figure 3b shows the complete meshed model where a denser mesh is used at the junction than at other parts. The length of the manifold (L_{st} + L_c) is 70

mm, and the length of the riser L_s is 30 mm. The effect of mesh density was checked for a mesh density of 7.4E5 and 3.7E6 cells/m^3 which showed a negligible effect on the results. The quality of the mesh was checked based on the criteria of equiangular skew (QEAS) and equalize skew (QEVS). For more than 90% of the volume, the QEAS and QEVS are lower than 0.4, which refers to a good quality mesh.

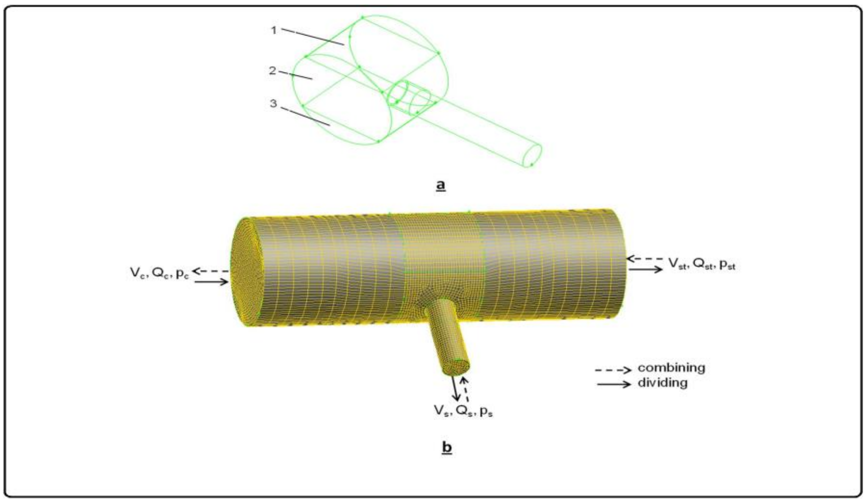

Figure 3: Schematic meshed model. (a) Portion of junction separated into three parts in order to have a regular mesh. (b) Meshed model of the manifold and riser, with higher mesh density at the junction.

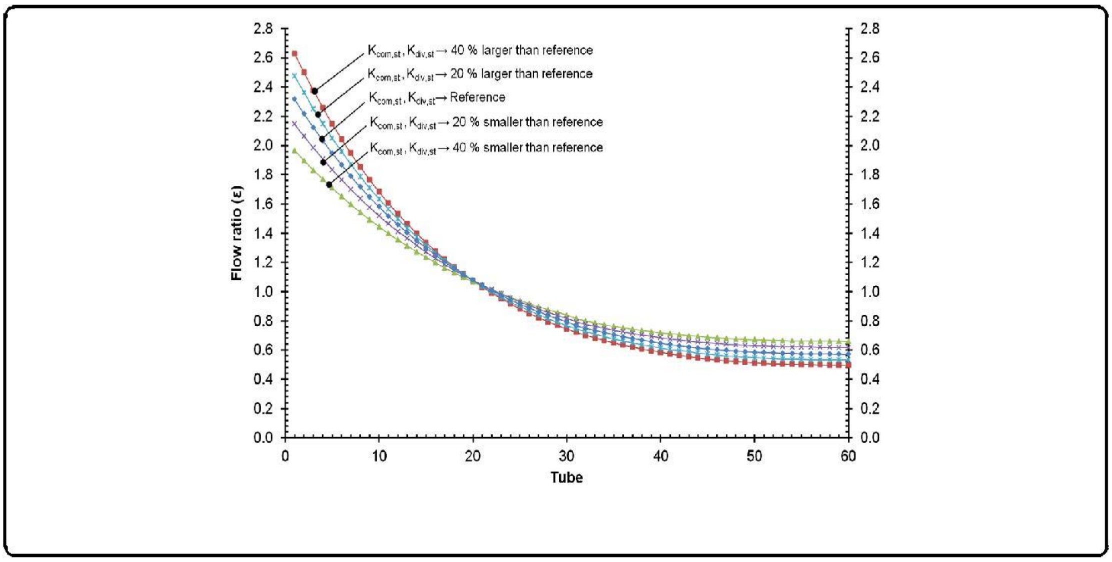

Figure 4: Isothermal flow distribution at M = 78 kg/m^2 h for U-configuration by varying $k_{div,st}$ and $k_{com,st}$. The distribution is in the range of −40% to 40% of the reference.

($k_{div,s}$ and $k_{com,s}$) have a marginal effect on the flow distribution by increasing or decreasing it in the range of −40% to +40%, while the straight flow coefficients result in a higher deviation from the reference case in the same range , but still, the deviation is not so drastic from the reference. This can be explained in a way that, for example, a fluid particle which is flowing through the 30th riser has to encounter 29 straight flow junction losses ($k_{div,st}$ and $k_{com,st}$) in the dividing and combining manifolds and only two side flow junction losses ($k_{div,s}$ and $k_{com,s}$) in the 30th riser. It can be concluded that straight flow junction loss coefficients are more critical in finding the correct flow distribution.

3. RESULTS

The CFD-based model is now used to investigate various aspects of the flow distribution mechanism.

Figure4 illustrates the comparison of the calculated flow distribution based on the junction loss coefficients from CFD simulations at low Reynolds numbers and the available correlations for turbulent flows from Idelchik and Bassett. It is seen in Figure 4 that the resulting flow distribution curves for Idelchik and Bassett are almost identical but differ appreciably from the present case. The main reason for this deviation is the low values of the junction loss coefficients of the straight flow ($k_{div,st}$ and $k_{com,st}$) from the correlations of Idelchik and/or Bassett depicted in for the encountered range of Reynolds number from 70 to 7,000 (corresponding to total mass flow of 78 kg/m^2 K) in the manifolds.

Shows the flow distribution for increasing length of the riser while keeping the geometrical

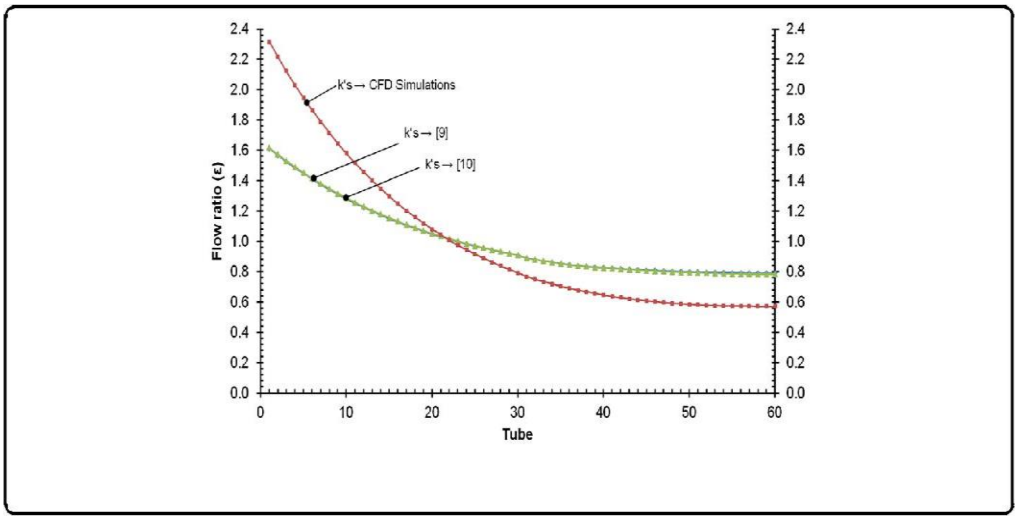

Figure 5: Comparison of isothermal flow distribution (U-configuration) for junction loss coefficients.

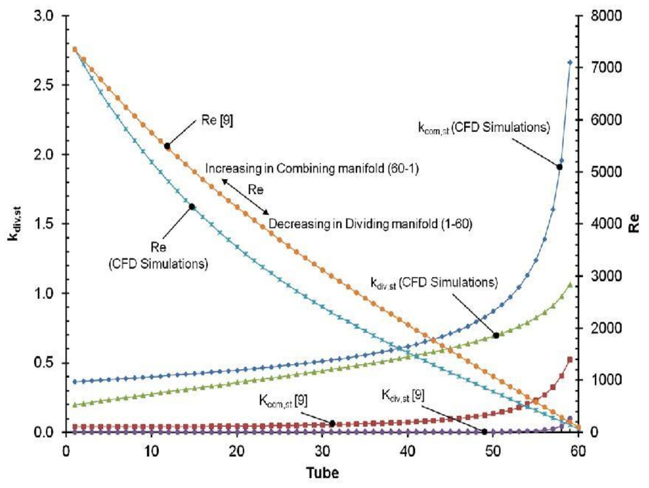

Figure 6: Variation of $k_{div/com,st}$ at each branch of dividing and combining manifold. Based on CFD simulations Idelchik [9] for U-configuration at M = 78 kg/m^2 h.

Parameters of the manifolds the same (see Table 1).It is obvious that flow uniformity increases with increasing riser length from 1.82 to 8 m, which leads to a well-known principle regarding flow distribution in manifolds, i.e., higher pressure drop in the risers as compared with the manifolds results in more uniform flow distribution.

Finally, the flow distribution is also calculated for the Z-configuration, and comparison is made for the same collector connected in the U- and Z-configurations (Figure 8). For the Z-configuration, the flows are higher at the ends and lower in the middle tubes; they show a similar trend as predicted by McPhedran for 60 tubes and also in good agreement with the experimental results of Glembin [6]. The Z-configuration results in more uniform flow (E is near to unity). The minimum flow ratio E and thus the minimum riser flow rate reached in the case of the Z-configuration (0.8) is 20% higher than for the case of the U-configuration (0.6). However, even in Z-configuration, the flow distribution is not at all uniform.

4. CONCLUSIONS

A CFD analysis is used to estimate the junction losses at the tee junctions of a collector manifold. A simplified model of the junction is built and simulated in FLUENT for a range of Reynolds numbers and riser-to-manifold flow ratios. The resulting junction loss coefficients have

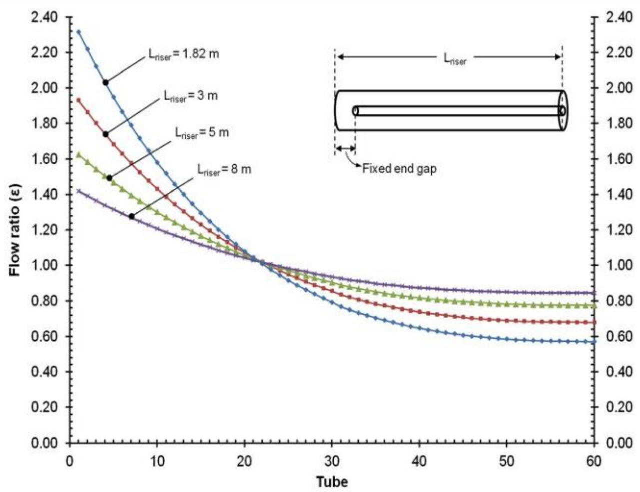

Figure 7: Isothermal flow distribution with increasing riser length for U-configuration at M= 78 kg/m^2 h.

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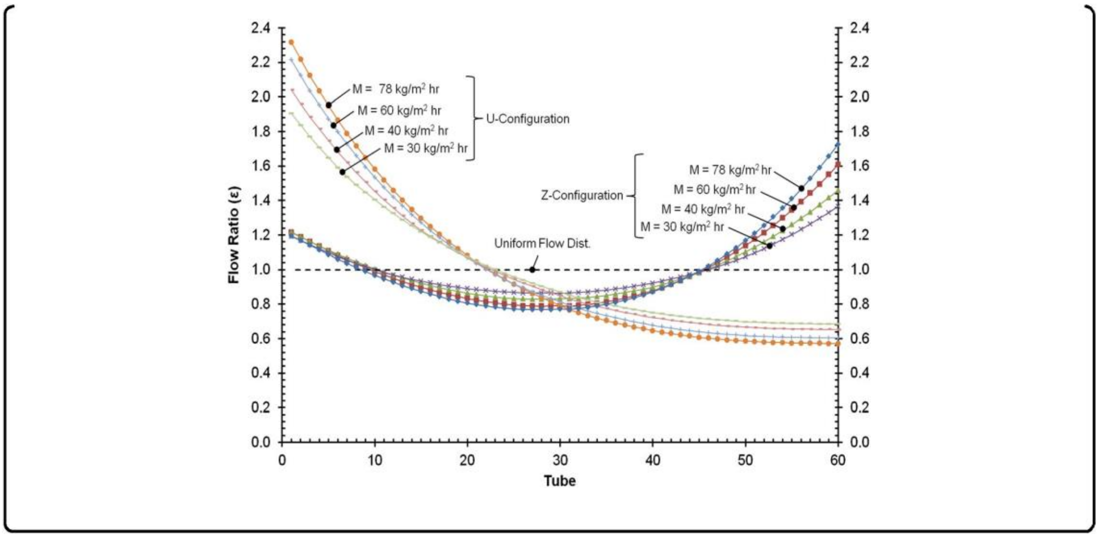

Figure 8: Isothermal flow distribution curves for U- and Z-configuration.

Shown a strong dependency on the flow rate at low Reynolds numbers

The variable loss coefficients are implemented in a theoretical model to predict the flow distribution in a co-axial vacuum tube solar collector arranged in U- and/or Z-configurations. The model is validated with the experimental results for the same collector in U-configuration. The model agrees reasonably well (but not perfectly) to the experiments. The model can be used to predict flow distribution for any number of risers in the prescribed range of Reynolds numbers. Flow uniformity decreases with increasing flow rate and temperature. Parallel flow (Z-configuration) results in more but not perfectly uniform flow than the reverse flow (U-configuration). The proposed CFD-based method can replace the expensive and time-consuming procedure of setting up experiments for estimating junction losses.

Abbreviations:

Nomenclature:

D: Diameter (m); F: moody friction factor (–); $h_i - h_o$: head loss (m);

I: turbulence intensity; K: pressure loss coefficient (–); $k_{com,s}$: local pressure loss coefficient for combining side flow (–); $k_{com,st}$: local pressure loss coefficient for combining straight flow (–); $k_{div,s}$: local pressure loss coefficient

for dividing side flow (–); $k_{div,st}$: local pressure loss coefficient for dividing straight flow (–); L: length (m); P: pressure (Pa); p: pressure drop

Manifold in combing flow (Pa); Q: volume flow (m^3/s);

Q_o: total volume flow (m^3/s); R: frictional resistance (s^2/m^5); R_c: frictional resistance for the flow through dividing or combining manifold in U-configuration (s^2/m^5); R_{dm}: frictional resistance for the flow through dividing manifold in Z-configuration (s^2/m^5); R_{cm}: frictional resistance for the flow through combining manifold in Z-configuration (s^2/m^5);

$R_{j,div,s/st}$: junction resistance for the side or straight flow in dividing manifold

(s^2/m^5); $R_{j,com,s/st}$: junction resistance for the side or straight flow

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

AWB developed and programmed the numerical model for calculating the flow distribution and drafted the manuscript. RB collected the data, conducted the initial study, carried out initial analysis, and participated in the design and coordination of the study. YL participated in the design of the study, constructed the model geometry for simulation, performed simulations, and developed equations to be used in the numerical model. FZ checked the whole work critically and edited and corrected the draft manuscript. All authors read and approved the manuscript.

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