Effect of tapered headers on pressure drop and flow distribution in a U-type polymeric solar absorber

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ABSTRACT

This study inspects the effect of tapered headers on pressure drop and flow distribution in a U-type polymeric absorber with novel tapered headers and lens-shaped absorber strings using a validated thermo-hydraulic model. The model results are compared with those obtained from the literature to attain credibility in the flow distribution trend for the U-configuration. A good agreement between the developed discrete model and comparison cases is found. Moreover, in order to examine the efficacy of tapered headers in more detail, different scenarios are treated in terms of header configurations. A good agreement between the developed discrete model and comparison cases is found. Moreover, in order to examine the efficacy of tapered headers in more detail, different scenarios are treated in terms of header configuration by applying cylindrical geometry in one or both inlet/outlet headers. The outcomes exemplify that even a slight cone angle of 1.73° in headers can significantly reduce non-uniformity (ϕ < 8%) with negligible influence on the total pressured drop. Yet, further reduction in maldistribution (ϕ < 5%) can be achieved in U-type absorbers if the tapered outlet header is combined with a cylindrical inlet header in the range of AR ≤ 3.34 and DR ≤ 0.24. In this case, a compromise between additional pressure drop and flow distribution degree should be found. The present study offers a systematic approach for conducting thermo-hydraulic analysis in flat-plate solar collectors with complex absorber compositions and geometries.

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1. Introduction

Long-term energy demand is expected to grow worldwide, keeping pace with rapid economic development [1]. Nowadays, sustainable and renewable-oriented development is not just a prerequisite to reducing the global carbon footprint [2]; it is also a pressing need to find dispatchable and pollution-free alternatives to depleting conventional fossil resources in order to fulfill the growing energy demands in the coming years [2]. Renewable technologies portray a reliable pathway toward a sustainable and CO2-neutral future. Amongst renewables, solar energy is a promising source with different applications such as space heating and cooling, domestic hot water, power generation, and desalination [3]. IEA reports reveal that in 2020, 50% of global final energy consumption was thermal-based, of which only 11% was covered by modern renewables [4]. In addition, 47% of the global supplied heat in 2020 was consumed in the building sector for space and water heating purposes. Such data indicates the massive yet not fully utilized potential for solar thermal technologies to contribute to energy sustainability targets and decarbonization scenarios.

A flat-plate solar collector (FPC) is a parallel-flow heat exchanger specifically designed to harness and convert radiant energy into heat for different thermal applications, including space heating and domestic hot water [5]. The FPC is the most widely used solar thermal technology in Europe for low-temperature (<100 °C) applications [6] due to its simple structure and relatively low cost [7]. Yet, low thermal efficiency is the major downside of FPCs [8], leading to numerous research efforts to enhance their performance [9]. Further, flow imbalance in FPCs can deteriorate thermal performance due to different outlet temperatures in parallel tubes supplied with different flow rates. Thus, the hydraulic features of FPCs play a significant role in thermal performance. Literature classifies the most prevalent types of FPCs into Z-type and U-type in terms of header configuration, as shown in Fig. 1. Flow distribution in FPCs can only be improved by altering geometry in headers and risers. The geometrical features by which flow distribution in FPCs can be evaluated are typically characterized in literature by dimensionless parameters such as riser-to-header diameter ratio (DR) and area ratio.
Further, using polymers can considerably increase the cost-benefit of solar collectors, especially at the absorber level, as this alone accounts for approx. 50% of the total cost in conventional FPCs with metal absorbers [10]. Yet, the low thermal conductivity of polymers (i.e. 0.1–0.5 W/(m.K)) compared to metal absorbers (e.g. copper 483 W/(m.K)) is a significant challenge for researchers and engineers to reach the desired thermal performance [11]. The direct heat-exchange surface between absorber plate and heat carrier in polymer absorbers is typically enhanced by minimizing the intervals between side-by-side riser tubes. However, this approach inevitably results in larger area ratios (AR) in polymeric absorbers than metal ones, responsible for a high degree of maldistribution and thus poor thermal performance [12]. In metal absorbers, risers and headers are often produced in cylindrical shapes. In contrast, polymeric absorbers can be favorably formed into other geometries to alter flow distribution characteristics, given higher manufacturing flexibility by polymers. In this context, the polymeric absorber in this study takes advantage of this flexibility to examine novel geometries in headers and risers in order to achieve a practical solution to the maldistribution problem mentioned above.

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2. Literature review
2.1. Background

This study deals with the flow distribution in a U-type absorber with tapered headers using a validated discrete model by which a hydraulic domain is split into several pressure nodes where pressure difference values are calculated using empirical correlations. Such correlations are convenient to use by scientists and engineers and can be easily found in fluid dynamics handbooks (e.g. Refs. [13,14]). Note that in discrete models, the fluid flow in all hydraulic components is assumed to be fully developed as an intrinsic measurement condition under which such empirical equations are derived. In this context, the present study engages with applying a validated discrete model to evaluate the flow distribution in a U-type flat-plate absorber with tapered headers.

2.2. Flow distribution in flat-plate solar collectors

Research on parallel flow distribution has a long tradition in the literature and has spun out into solar thermal applications such as
flat-plate collectors for decades. It is common knowledge that flow non-uniformity in FPCs can lead to technical challenges such as partial boiling and mechanical failure due to overheated spots [15,16] and poor efficiency due to different outlet temperatures in riser tubes. In this context, Chio [17] conducted one of the first attempts to show how maldistribution affects thermal performance. The study reported efficiency decay in the range of 2%–20% depending on the hydraulic features of solar absorbers. For such thermal assessments, thermo-hydraulic models are essential to determine the actual distribution status in the parallel tubes. When it comes to glazed polymeric collectors, the reduction in the non-uniformity is a crucial prerequisite for innovative methods that aim to enhance thermal performance (e.g. use of nanofluids/nanocomposites [18], variable flow rates/tilt angles [19]).

Wang and Wu [20] studied flow distribution in solar collectors with U-type and Z-type configurations. They found an overall more uniform flow distribution in Z-type absorbers than the U-type due to reverse connections in the outlet header. According to Dhahad et al. [12], U-type absorbers are prone to higher non-uniformity but slightly lower pressure drop than the Z-type with identical risers because of the proximity of the inlet and outlet connection and significantly different lengths of hydraulic paths from the first to the last riser tube. On their part, Jones and Lior [21] reported the same trend by analytical models for Z and U configurations under isothermal conditions. They showed that in U-type absorbers flow rate in riser tubes decreases monotonically with the distance from inlet/out when the flow regime in headers is turbulent. It was also found that the flow distribution is greatly affected by the riser-to-header-diameter ratio (DR) and the number of riser tubes (nr). A similar flow distribution pattern for the U-type arrangement can be noticed in the results of Datta and Majumdar [22], whereby the role of large area ratios (AR) on deteriorating flow uniformity was accentuated. Both studies [21,22] dealt with fully turbulent regimes overlooking the influence of transitional flows in headers on flow distribution.

Weitbrecht et al. [23] carried out an analytical and experimental investigation on flow distribution in a Z-type absorber considering a small riser tube inset (4.5 mm) into headers. Along with confirming the results of [20,21], the work argued that the flow maldistribution is sufficiently low in Z-type absorbers, provided that the pressure losses in riser tubes remain much higher than those in headers. However, Bava et al. [24], investigating the influence of flow regime in headers on flow distribution, argued that the conclusion of [23] can be held valid only when the flow regime remains entirely turbulent with no transition occurring in both headers. The work presented a discrete model for evaluating flow distribution in a U-type solar collector by employing the so-called linear theory [25], whereby the flow rate of each hydraulic path is linearized subject to the calculated flow rate from the previous iteration. On their part, Fan et al. [15,16] studied temperature distribution in solar collectors driven by flow maldistribution. They argued that buoyancy plays a role only at low flow conditions coupled with significant temperature rise in absorber pipes induced by high radiative heat flux during incipient stagnation. Apart from this, Dunkle and Davey [26] found that the non-uniformity induced by natural circulation (i.e. laminar flow) is comparably lower than that by forced circulation (i.e. turbulent flow).

Further, Missirlis et al. [27] proposed aligning inlet/outlet pipes with riser tubes for better flow distribution. However, it is doubtful if this approach can be generalized to other FPC designs. Guendulain et al. [28] reported up to 40% flow distribution betterment using small plates in headers to alter flow distribution patterns. Though such plates can increase the risk of dirt clogs in the absorber during long-term operation. Facao [29] validated a CFD model against calculated flow rates from measured pressure differences in absorber tubes. The study suggested a larger outlet header in Z-type absorbers for better flow distribution. However, the diameter difference between headers was not characterized in terms of area ratio and diameter ratio. In contrast, García-Guendulain et al. [30], with the aid of an analytical model, recommended AR ≤ 0.75 and DR ≤ 0.25 for obtaining a more uniform flow distribution in both Z-type and U-type absorbers. It can be argued that in polymeric absorbers with many side-by-side risers and thus large area ratios, the criteria mentioned above resulted in overly large headers compared to the aperture area of the absorber.

More recently, Shantia et al. [31] investigated the effect of tapered headers on the flow distribution in a Z-type polymeric solar absorber. This work was motivated by the lack of knowledge on how tapered headers affect flow distribution in FPCs despite the considerable body of literature in which commonly constant cross-section area in headers was considered. The work compared the performance of tapered headers with typical cylindrical ones of different diameters. It was shown that even a slight cone angle in headers could significantly reduce maldistribution by maintaining higher fluid velocities and thus preventing sharp flow regime variations. However, these findings are only applicable to Z-type absorbers.

2.3. Contribution of this work

In this work, a validated model from Ref. [31] is further employed to examine the effect of tapered headers in a U-type polymeric absorber. To the authors’ knowledge, no such study on tapered headers for U-type FPCs exists in the literature. Further to the former work confirming flow distribution improvement in a Z-type polymeric absorber using tapered headers [31], the present work inspects a similar polymeric absorber, but this time with the U-type configuration. Since the interplay between flow maldistribution and thermal performance in solar collectors is already well-established in the literature, this work solely focuses on detailed thermo-hydraulic aspects and does not directly engage with thermal performance evaluation.

This work first describes a validated thermo-hydraulic model developed to inspect flow distribution in solar absorbers with tapered headers. Second, the model's reliability in terms of flow distribution for the U configuration is further verified by comparing its results with previous literature. Later, different scenarios are treated to compare the original model (with both tapered inlet and outlet headers) against other cases with identical absorber strings and cylindrical headers of different diameters. Finally, the paper is wrapped up by discussions together with conclusions and future perspectives.

3. Material and methods

3.1. Polymer absorber

Fig. 2 shows the scheme of the investigated absorber, and Table 1 reports its relevant geometrical parameters. The U-type polymeric absorber with lensed-shaped absorber strings and tapered headers is 958 mm long and 463 mm wide. Its 33 absorber tubes are 927 mm long, have a hydraulic diameter (D_	ext{hyd}) of 3.84 mm and an intermediate spacing of 3.5 mm to enhance the direct heat exchange surface between the working fluid and the absorber exterior surface. The diameter of its tapered header varies linearly from 22 mm (D1) at the inlet down to 8 mm (D2) near the 33rd string giving a convergence angle of 1.73°. Further information on the studied absorber can be found in Table 1.
3.2. Mathematical model

The discrete model developed and validated in Ref. [31] is further employed to inspect the U-type polymeric absorber. Both the U-type and the Z-type polymeric absorbers share identical geometrical features (i.e. absorber dimensions, AR, DR, and header cone angle) and the same governing equations in absorber strings, mixing/diverting tees, and conical contractions/expansions in the headers for thermo-hydraulic calculations. Nevertheless, the system of equations in each case is configured differently based on the connectivity of components in the headers, riser tubes, and inlet/outlet. Consequently, the validated model for the Z-type absorber can also be used to inspect the U-type absorber.

In discrete models, empirical pressure drop correlations for laminar and turbulent flows are often used along with the Bernoulli equation. In this approach, the total pressure drop in each hydraulic component (i.e. tees, conversions, and riser tubes) is the sum of surface friction loss due to viscous effects and fluid shear stress at the pipe wall and local loss (ζ) due to local disruptions and direction change of the fluid stream. Consequently:

$$\Delta p_{\text{tot}} = \Delta p_{\text{fr}} + \Delta p_{\text{loc}}$$  \hspace{1cm} (1)

where $\Delta p_{\text{fr}}$ and $\Delta p_{\text{loc}}$ denote the frictional and the local losses, respectively. In this context, the hydraulic elements in the investigated absorber include 33 lens-shaped riser tubes, 66 smooth-edged diverging/converging tee junctions, and 66 conical contractions/expansions, as shown in Fig. 3. In addition to the hydraulic components, Fig. 3 also depicts the pressure nodes involved in thermo-hydraulic calculations in the developed model. The considered length of diverging/converging tees in the tapered headers is relatively short (i.e. 2.0 mm), adjoined by conical contractions/expansions in the middle with a length of 11.5 mm.

Further, the laminar-to-turbulent transient region is included in the thermo-hydraulic model for numerical continuity. The transient frictional loss in hydraulic components is evaluated by linear interpolation between the corresponding values at the upper and the lower of the transition range in terms of the Reynolds number. Similarly, the transient local losses in tees and conversions are evaluated using relevant laminar and turbulent correlations. The same range for transitional flow as for the Z-type absorber, $1000 \leq \text{Re} \leq 2200$, is assumed for the U-type, given identical geometrical features (i.e. absorber dimensions, diameter ratio, area ratio, header cone angle, and riser tube intervals) in both configurations.

The numerical algorithm used herein is tailored to complex thermo-hydraulic evaluations. It consists of systems of non-
headers. ARavg cross-sectional area and diameter of the maldistribution intensity in parallel tubes, the dimensionless in Table 1 using Eqs. (2) and (3). Further, in order to quantify the maldistribution intensity in parallel tubes, the dimensionless flow rate \( (a_i) \) and the non-uniformity \( (\varphi) \) are defined, which are governed by the following equations:

\[
AR_{avg} = A_f \left( \sum_{i=1}^{nr} A_{h,i} \right) / nr
\]

\[
DR_{avg} = D_t \left( \sum_{i=1}^{nr} D_{h,i} \right) / nr
\]

where \( nr \) and \( m_i \) represent the total number of the riser tubes and the mass flow rate in the \( i \)-th riser, respectively, whereas \( d_{avg} \) is the average dimensionless flow rate \( (d_{avg} = (\sum_{i=1}^{nr} a_i)/nr) \). Note that the ideal and perfect uniform flow distribution in a flat-plate absorber is expressed by dimensionless flow rates of unity \( (a_i = 1) \) in all riser tubes resulting in a non-uniformity of null \( (\varphi = 0) \), as given by Eq. (5). It can be noted that the greater the deviation of \( a_i \) from unity (or \( \varphi \) from null), the higher the maldistribution degree in the \( i \)-th riser tube (or the entire absorber).

4. Results

The flow distribution in the U-type absorber can be investigated using the model developed and validated in Ref. [31]. In order to demonstrate the reliability of the result of the model regarding its agreement with the general flow distribution pattern in conventional U-type absorbers with cylindrical headers, further comparisons were performed against the existing literature, i.e. simulation results from Jone and Lior [21]. Finally, different scenarios were treated in terms of header configuration by applying cylindrical geometry in one or both inlet/outlet headers in order to inspect the efficacy of tapered headers in more detail.

4.1. Comparing the flow distribution pattern with previous literature [21]

Given the novelty of the investigated absorber and in light of the lack of similar studies in the literature on tapered headers, the analytical study by Jone and Lior [21] was chosen for comparison due to its similar application (i.e. solar collector) and the reliability of its results confirmed in two subsequent studies [23,32]. Two conventional U-type absorbers with 8 and 16 riser tubes and cylindrical headers were considered from Jones and Lior’s work for comparison, similar to that shown in Fig. 1(b). The length and diameter of the riser tubes in both cases are 1.83 m and 6.35 mm, respectively. Further, the axial distance between two adjacent strings is 76 mm, and the diameter of the inlet and outlet header is 25.4 mm in both cases. The transient region assumed in Jones and Lior’s work is for 2100 < Re < 3000. The friction factors are evaluated in the model by Hagen-Poiseuille for Re < 2100, Colebrook equation for Re > 3000, and linear interpolation between the two in the transient region. The pressure loss in tees is estimated based on constant pressure regain coefficients (i.e. \( \gamma = 0 \) for converging tees and \( \gamma = 0.9 \) for diverging tees) irrespective of the flow regime.

Heat transfer fluid is water at 60 °C and a total flow rate of 5.46 lิต min⁻¹ corresponding to a Reynolds number of 9640 at the inlet. In this study [21], it is declared that the roughness of inner surfaces is in the middle range between smooth copper tubes and steel pipes, but no explicit value was given. Hence, a roughness of 0.025 mm was assumed for reproducing the results. Similarly, a radius ratio of 0.1 was assumed in the present model for tee junctions, which is standard in industrial products [14].

Fig. 4 compares Jones’s results and the present model for both cases. The present model is deemed to be in good agreement. The highest relative difference between the two models is well within 4.6% and 1.5% in the cases with 8 and 16 pipes, respectively.

![Fig. 3. Nodal pressures calculated in the discrete model.](image-url)
Considering Fig. 4, the typical flow distribution pattern for U-type absorbers under turbulent flow conditions can be recognized. In this case, the closer a string to the absorber inlet/outlet, the higher the dimensionless flow rate and hence the maldistribution degree. It can also be noted that the present model predicts somewhat more uniform distributions in both cases than Jones’s.

4.2. Flow distribution in the polymer absorber

Fig. 5 shows the resulting dimensionless flow rates in the polymeric absorber for water at 60 °C and total flow rates ranging from 0.05 to 0.95 m³ h⁻¹. It can be noted that at the lowest flow rate (0.05 m³ h⁻¹), the distribution trend gives underflows (α < 1) in the first half (closer to inlet/outlet) and overflows (α > 1) in the second half of the absorber. As the flow increases (>0.05 m³ h⁻¹), the imbalance is rapidly suppressed and turns to overflows in the first half and underflows in the second half of the strings. The imbalance keeps its growing trend up to the middle range flows (approx. 0.15–0.20 m³ h⁻¹), which coincides with an abrupt change in the dimensionless flow rate in the last strings (i.e. from 29th to 33th). However, further flow increase (>0.269 m³ h⁻¹) improves the imbalance noticeably, giving rise to a smooth distribution trend in both halves of the absorber.

In addition, Fig. 6 illustrates the non-uniformity development in the polymeric absorber for water temperatures ranging from 20 °C to 80 °C. The non-uniformity (see Eq. (5)) characterizes the intensity of imbalance in riser tubes by a single value for a specified total flow rate and mean temperature. The results indicate that a higher temperature always entails fewer non-uniformity oscillations up to the middle range flows (approx. <0.46 m³ h⁻¹) and thus faster transition to the next stage at which the non-uniformity is almost constant and independent from the flow rate. Fig. 6 also illustrates a slight increase of non-uniformity with temperature in this relatively stable region.

4.3. Investigated scenarios for header configuration

This study aims to ascertain the efficacy of tapered headers on flow distribution in polymeric absorbers with relatively large area ratios. For this reason, different scenarios are treated in terms of header configuration to study the pressure drop and flow distribution trends in more detail. The composition of the riser tubes is the same in all scenarios as in the original case with tapered headers while considering cylindrical headers of various diameters in one or both headers. These comparison scenarios are summarized in Table 2. Note that all simulation results in this section are presented for water at 60 °C.

4.3.1. Case 1: cylindrical inlet/outlet headers of the same diameter

This case consists of subcases 1.1 to 1.8 with identical cylindrical headers from 12 mm to 18 mm and 2 mm increments. Fig. 7 compares the calculated pressure drop of these subcases with the original case (i.e. tapered inlet/outlet header). In general, as expected, the smaller the header, the higher the total pressure drop. It is also observed that subcase 1.1 (Dh = 12 mm, AR = 5.94, DR = 0.32) produces much higher pressure losses than the others. At low flow rates up to 0.22 m³ h⁻¹, the pressure-flow dependence is approximately linear, with no distinctive pressure drop variations in all cases. This trend, however, transforms into the typical quadratic relation with noticeable differences as flow increases further. The results for the tapered case are more comparable to subcase 1.4 (Dh = 18 mm, AR = 2.64, DR = 0.21) at low flows, subcase 1.6 (Dh = 22 mm, AR = 1.77, DR = 0.17) at intermediate flows, and subcase 1.2 (Dh = 14 mm, AR = 4.36, DR = 0.27) at higher flows.

Further, the resulting non-uniformities in case 1 are revealed in Fig. 8. It can be seen that at low flow rates (<0.25 m³ h⁻¹), the non-uniformity increases in proportion to header diameter for Dh ≥ 16 mm, indicating maldistribution growth by the decrease of the area ratio (AR) and diameter ratio (DR). On the other hand, an overly small header (e.g. Dh = 12 mm) can also lead to poor flow distribution in the entire flow range. Moreover, it can be noted that tapered headers give noticeably better flow distribution for flow rates up to 0.25 m³ h⁻¹. At this point, a sharp drop is observed in all cases, followed by different increasing or decreasing trends for higher flows depending on header diameter. From the middle range on (>0.25 m³ h⁻¹), the tapered case and subcase 1.3 (Dh = 16 mm, AR = 3.34, DR = 0.24) present relatively similar non-uniformities. As the flow increases further (>0.60 m³ h⁻¹), a stepwise decrease of non-uniformity is detected for Dh ≥ 18 mm, where larger headers always give slightly lower non-uniformities. However, this difference becomes negligible at very high flow rates.

4.3.2. Case 2: cylindrical inlet header/tapered outlet header

This case aims to determine how strong the impact of the outlet tapered header is on flow distribution while the inlet header diameter is kept constant. Fig. 9 illustrates the resulting pressure drop in subcases 2.1 to 2.8, both for low and high flows. A closer inspection of this figure reveals that all subcases produce quite similar trends except for subcase 2.1 (Dh,in = 12 mm, AR,in = 5.94, DR,in = 0.32), which gives much higher pressure loss than other
cases regardless of the flow rate. In this context, the pressure behavior of the original case is more closely similar to subcase 2.3 ($D_{h,in} = 16$ mm, $AR_{in} = 3.34$, $DR_{in} = 0.24$) in most of the flow range.

In addition, Fig. 10 presents the resulting non-uniformity in case 2. It can be noted that the flow distribution is more uniform also less influenced by flow variations in subcases 2.1 to 2.8 if the tapered concept is only applied in the outlet header. Herein, the extent to which the non-uniformity varies is strongly associated with the inlet header size so that smaller header diameters give progressively lower maldistribution coupled with weaker dependence on flow variations in the entire range. Hence, the tapered shape of the outlet header plays a crucial role in reducing non-uniformity. Nevertheless, this improvement is penalized by increased pressure drops (and hence higher pumping power) while decreasing the inlet header diameter, as shown in Fig. 9. A similar trend in terms of non-uniformity can be observed between the original case and the most oversized inlet header (i.e. $D_{h,in} = 26$ mm, $AR_{h,in} = 1.27$, $DR_{h,in} = 0.15$). Since the simultaneous reduction of pressure drop and non-uniformity is not possible in this case, a compromise between the two needs to be found.

4.3.3. Case 3: tapered inlet header/cylindrical outlet header

In case 3, a reverse configuration in headers compared to case 2 is considered to study flow distribution in more detail when the tapered geometry is only used in the inlet header. Fig. 11 illustrates the resulting non-uniformities in subcases 3.1 to 3.8. Comparing these results with case 1 reveals very similar performance at low flow rates ($<0.25$ m$^3$ h$^{-1}$) in both cases but more intensified maldistribution at higher flow rates in subcases 3.1 to 3.8 than in subcases 1.1 to 1.8. Since case 3 yields no compelling results in terms of flow distribution, presenting the pressure drop trend for this case is seen as insignificant.

5. Discussions

5.1. Comparison of flow distribution against previous literature [21]

From Fig. 5, an overall good agreement between the developed model and [21] can be seen for the flow distribution. This minor difference between the two models was mainly due to the assumption of constant pressure regain coefficients in tees in Jones’s model, which produced steadily decreasing distribution profiles. In contrast, the empirical correlations used in the current model allowed higher fractions of total flow rates in the very last strings, compensated by some flow decrease in the first half of the absorber.

### Table 2

Summary of comparison scenarios.

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<td>Inlet header ($D_{h,in}$)</td>
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<td>U</td>
<td>12 mm–26 mm$^{(1)}$</td>
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<tr>
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<td>U</td>
<td>12 mm–26 mm$^{(1)}$</td>
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<tr>
<td>3</td>
<td>3.1 to 3.8</td>
<td>U</td>
<td>tapered</td>
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$^{(1)}$ 2 mm increment.
5.2. Flow distribution in the polymer absorber (both headers tapered)

The distribution results presented in Fig. 5 depicted that the flow regime in the absorber (especially in headers) played a vital role in the flow distribution pattern, which was consistent with previous findings in Refs. [24,31]. At the lowest flow rate ($V = 0.05 \text{ m}^3 \text{ h}^{-1}$), the flow was fully laminar in the headers and risers, causing underflows in the first strings and overflows in the last ones due to higher frictional and local loss coefficients in the components under laminar conditions. Further flow increase (up to 0.18 m$^3$ h$^{-1}$) resulted in turbulent conditions in some header segments, followed by a transition to laminar as the fluid flow decreases monotonically with distance from the absorber inlet. Hence, the abrupt changes in the dimensionless flow rate (e.g. at 0.15 and 0.18 m$^3$ h$^{-1}$) stemmed from the flow regime switched to transition and then laminar in the last strings (i.e. from 29th to 33rd). In this context, tapered headers can effectively mitigate the impact of transitional flows by maintaining higher velocities in the very last segments of the headers.
From Fig. 6, it can be argued that the temperature dependence of the kinematic viscosity induced a faster transition to turbulence and lower pressure drop at higher temperatures. In the investigated absorber, the pressure loss in parallel riser tubes accounted for a minimum of 80% of the total pressure drop. Hence, apart from the flow regime in the headers, the pressure drop portion in tubes compared to headers was another determining factor in achieving a more uniform flow distribution. This finding corroborated the results of [23,24], in which the effect of flow regime in headers on flow distribution was highlighted. For each temperature range, the onset of the turbulent-dominant regime in the absorber can be discerned by alleviated and relatively constant non-uniformities ($\varphi \approx 5\%$) by further flow increase. The faster pressure drop decrease in the risers than in headers (resulting from higher temperatures) contributed to slightly higher non-uniformities at high flow rates. Finally, the non-uniformity was relatively low ($\varphi < 2\%$) at the lowest flow rate ($V = 0.05 \text{ m}^3 \text{ h}^{-1}$) when the flow was laminar in all components reaching its maximum ($\varphi = 8\%$) when most of the segments in both headers were in transition. This low non-uniformity under laminar low flow conditions was comparable to natural circulation and agreed with the finding in Ref. [26].
5.3. Investigated scenarios for header configuration

The pressure drop trends in case 1 (with cylindrical inlet/outlet headers) and case 2 (with cylindrical inlet header/tapered outlet header) indicated that, as expected, overly undersized cylindrical headers ($D_h \leq 12$ mm, $AR \geq 5.94$, $DR \geq 0.32$) yield much higher pressure loss regardless of the flow range as the hydraulic resistance in headers became significant compared to those in riser tubes. In contrast, the impact of tapered headers on total pressure drop was proven to be negligible, as compared in Figs. 7 and 9. Apart from the pressure drop, the non-uniformity was noticeably improved and affected much less by the flow rate. In fact, the U configuration affected the flow distribution in two ways. First, significant differences in the length of hydraulic paths from one riser tube to another with the distance from the absorber inlet resulted in higher flow rates in the first risers to produce pressure balance despite shorter lengths. Second, variation of flow regime in headers as the fluid was monotonically distributed in the risers coincided in the similar segments of both headers.

Further, the resulting non-uniformities for case 2 (see Fig. 10) indicated a more prominent role of the tapered outlet header in achieving more uniform flow distributions. There were two main reasons for this behavior. First, the tapered outlet header maintained higher velocities reducing the risk of transition in the last segments. Second, it also prevented very high velocities in the straight side of mixing tees, which could otherwise intensify the flow rates in the first risers due to the Bernoulli effect in tees. Moreover, by comparing the non-uniformities in cases 2 and 3 (see Figs. 10 and 11), it can be realized that the application of tapered geometry on the inlet header (case 3) did not bring any advantage in terms of flow distribution. In particular, the most uniform flow distribution was obtained with a combination of cylindrical inlet and tapered outlet header.

Concerning the results shown in Fig. 10 for case 2, it was apparent that smaller inlet header diameters consistently resulted in more uniform flow distributions with slighter fluctuations in the entire flow range, but this was penalized by higher pressure drops at the same time. In this context, a slightly undersized inlet header such as subcase 2.3 ($D_{h,\text{in}} = 16$ mm, $AR_{h,\text{in}} = 3.34$, $DR_{h,\text{in}} = 0.24$) could entail an optimum outcome for both pressure drop and flow distribution when a single collector was considered. The main reason for the improved flow distribution in case 2 was higher local losses in diverging tees (especially those near the absorber inlet) resulting from higher velocities in the inlet header because of smaller diameters and hence reduced flow rates in the strings to which those tees were connected. Finally, a smaller diameter could also limit the transitional flows in the inlet header like the tapered header, but with pressure drop penalties.

6. Conclusions and future perspectives

In this work, a validated thermo-hydraulic model was employed to study flow distribution in a novel U-type polymeric absorber with tapered headers and lens-shaped riser tubes. The same transition region as in the Z-type model was assumed for the U-type. The results of the model were compared against the literature for flow distribution. An overall good agreement was found for flow distribution between the developed model and comparison cases. Additionally, in order to inspect the efficacy of tapered headers in more detail, different scenarios were conducted by applying it separately to each header, together with further comparisons with cylindrical headers using the developed model.

It was established that even a slight cone angle (of 1.73°) could significantly improve flow distribution with negligible effects on the total pressured drop. The main finding of this work was that further improvement in flow distribution was attainable in U-type absorbers if the tapered out header was combined with a slightly undersized cylindrical inlet header in the range of $AR_{h,\text{in}} \leq 3.34$ and $DR_{h,\text{in}} \leq 0.24$, considering the penalized pressure drop depending on the diameter. In other words, a higher pressure drop in the inlet header due to a smaller diameter could further improve flow distribution characteristics in U-type absorbers. In this regard, a compromise between pressure drop rate and flow distribution degree should be found for each design case depending upon boundary conditions, e.g. the nominal flow rate of a single collector or the maximum number of collectors expected to be installed in series in a collector array. Moreover, given a wealth of empirical correlations readily accessible in literature for different components and flow conditions, the model can be reliably used to conduct complex thermo-hydraulic analyses. In modern solar thermal systems, the control strategy continuously regulates the total flow rate in proportion to solar irradiance and the desired target temperature [32]. In such conditions, tapered headers ensure proper flow distribution and hence energy-efficient part-load performance.

The present study offers a pragmatic approach for conducting thermo-hydraulic analysis for FPCs with complex geometries using empirical correlations. In this line of work, future assessments include studying the influence of the header divergence angle on flow distribution and pressure drop in FPCs.
CRediT authorship contribution statement

**Alireza Shantia:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Visualization, Writing – original draft. **Wolfgang Streicher:** Writing – review & editing. **Chris Bales:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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