Mesh independency study for an unglazed transpired solar collector

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Abstract. Transpired solar collectors have been widely studied during the last 30 years by experimental, mathematical, and numerical approaches. However, numerical approaches have been frequently simplified because of insufficient computing power. Transpired solar collectors are complex to analyze via numerical simulation mainly due to a difference in scale between the very small holes on the absorber plate and the entire collector size. Thereby, the aim of this paper is to analyze the independency of high-resolution meshes for a longitudinal slice of an entire transpired solar collector and to determine a proper geometrical discretization leading to a good accuracy of the numerical results in a reasonable computing time. This study has shown the importance of the mesh size and refinement in order to capture the thermal and flow characteristics inside unglazed transpired solar air collectors. The obtained results highlight the fact that even with the lowest size of mesh the outlet temperature and temperature variation inside the solar collector is despite everything close to the finest mesh. Thus, for global analysis of a simple solar collector a coarse mesh could be sufficient. However, an increase in the mesh size it has an influence on the temperature and velocity profiles behind the perforated absorber plate.

1. Introduction

The building sector is the biggest energy consumer and greenhouse gas emissions contributor in the world. It is still representing 36% of the final global energy consumption and 40% of the greenhouse gas emissions, being critical to reduce the energy consumption of the building sector in the coming years.

Since 2010, the European Union has established policies including Energy Performance of Buildings Directive 2010/31/EU (EPBD) and Energy Efficiency Directive 2012/27/EU (EED) to improve the building sector in European Union. These policies have been strengthened first in 2018 (2018/844/EU) in the establishment of the Clean energy for all Europeans package to be in accordance with the Paris Agreement and then in December 2019 during the presentation of the European Green Deal. All these directives and policies are made to improve the energy efficiency and to decarbonize the building sector until 2050. By the end of 2020 early 2021 all new building should be Nearly Zero-Energy Buildings (NZEB) and in the near future to achieve Positive Energy Buildings (PEB) [1].

In order to achieve all these objectives new energy systems should be proposed and building architectures should be reconsidered. Some of the solutions are anchored in the building itself, and from these our attention is focused on the building envelope/facade. Building facades can harness large amounts of energy from the sun [2] and in recent years they have been widely studied often under the name of Building-Integrated Solar Thermal systems [3, 4].
In this wide group of Building-Integrated Solar Thermal systems we find the Transpired Solar Collectors (TSC). TSC can be glazed (GTSC) or unglazed (UTSC), they are usually implemented on large scale buildings, such as industrial, office or multi-families residential building for ventilation and space heating during cold period. This kind of solar air collector has the advantage of being cheap and easy to integrate for a building retrofit.

Transpired solar collectors have been widely studied during the last 30 years by experimental, mathematical, and numerical approaches. Computational Fluid Dynamics (CFD) studies on UTSC started in the late 90s with a 2D simulation conducted by Gunnewiek et al. [5]. This study has shown the importance of the heat transfer at the back of the perforated absorber plate. In another study [6], they upgraded their numerical model by adding the effect of the wind. Conclusions of this paper are very useful, indeed, Gunnewiek et al. demonstrated that a suction velocity should be maintain above 0.0125 to 0.039 m/s depending on the building type to avoid reverse flow. Another solution proposed by Gunnewiek et al. to mitigate the negative effect of the wind speed is to avoid perforations on the upper part of the collector.

In 2001, an important physical phenomenon for UTSC has been described by [7], they determined that total heat transfer is distributed in different parts of the absorber plate. The air temperature rise is distributed as such: 62% on the front, 28% in the hole and 10% on the back of the plate.

Then in 2002 Gawlik and Kutscher [8] continued the CFD study on the effect of the wind speed, suction velocity, and absorber plate shape. In the same year [9], they conducted a comparative numerical and experimental study of two different material type of absorber plate, plastic and aluminum, they concluded that the thermal conductivity of the absorber plate has no significant effect on the thermal performance of the UTSC.

All these CFD studies were useful for the understanding of UTSC however they had to face the lack of computing power and thus had to simplify their numerical model. Transpired solar collectors are complex to analyse via numerical simulation mainly due to a difference in scale between the very small holes on the absorber plate and the entire collector size. This makes it necessary to use higher growth rates than usual to be able to capture the physical phenomena both at the level of the holes and for the rest of the collector.

Nowadays the computing power has increased, and we are able to produce high definition numerical model. Thereby, the aim of this paper is to examine the independency of high resolution meshes for a longitudinal slice of an entire transpired solar collector and to determine a proper geometrical discretization leading to a good accuracy of the numerical results in a reasonable computing time.

2. Methodology

The aim of this study is to provide a high-resolution mesh to accurately capture the flow characteristics of different length scales in order to analyze the overall heat transfer along the perforated absorber plate and inside a back-pass UTSC. Unglazed Transpired Solar Collectors have been widely studied at the "Advanced Research Centre for Ambiental Quality and Building Physics" (CAMBI) present at

Technical University of Civil Engineering of Bucharest. Several types of perforations and optimizations have been investigated, such as lobbed holes for the perforated absorber plate and integration of phase change materials [10-14] .
The ANSYS meshing application part of commercial CFD software ANSYS 19.0 has been used to create 7 meshes with different number of cells 4, 7, 12, 18, 29, 32.5, 38 million cells. FLUENT has been used to solve the steady state conservation of energy, mass, and momentum. The three-dimensional geometry has been geometrically modelled in SOLIDWORKS software.

2.1. Geometry

Figure 1 show the prototype of unglazed transpired solar collector studied in this paper. This novel prototype of UTSC include a separation absorber plate used in one hand to prevent an air by-pass in the upper part of the collector and in the other hand to collect the residual solar radiation passing thought the holes of the perforated absorber plate. Due the this second absorber plate, this prototype of UTSC can be presented as a double-skin unglazed transpired collector. The UTSC prototype consist of a perforated absorber plate and a separation plate both made of aluminum with black coating, and a plywood-based frame with thermal insulation. As shown in the Figure 2, the geometry used for the mesh independency study consists only of a slice of the real size protype. This choice was made in order to reduce the size of the mesh which in the case of this slice is already large. Indeed, the prototype absorber plate is composed 5000 circular perforations of 5mm, the numerical study of such a complex geometry would require a large mesh and non-cost-efficient computation time and power. Therefore, we studied a longitudinal slice of the UTSC composed of 100 circular holes. Due to the geometric features of the studied geometry we consider that a numerical study performed only for this slice will be representative for the research carried out for the entire geometry.

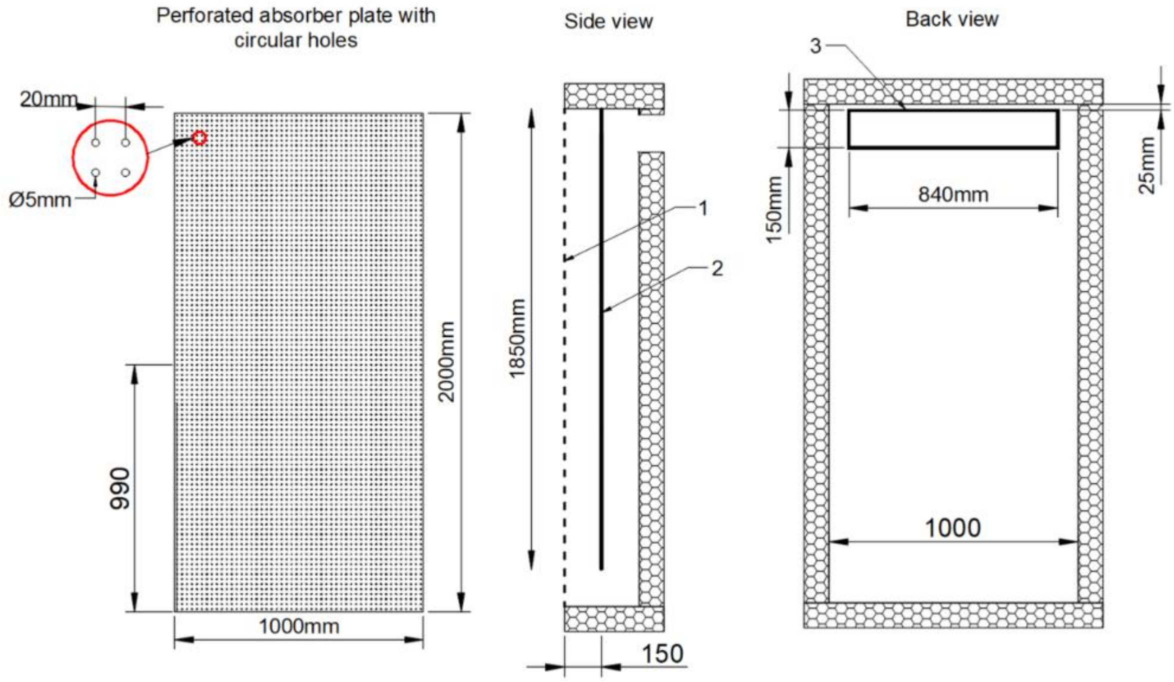


Figure 1 Scheme of the unglazed transpired solar collector protype. 1. Perforated absorber plate made of aluminum with black coating. 2. Separation plate made of aluminum. 3. Air outlet.

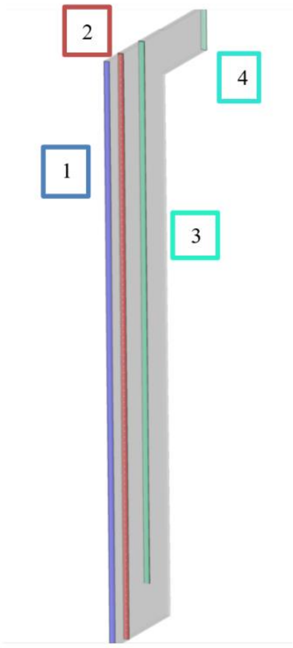
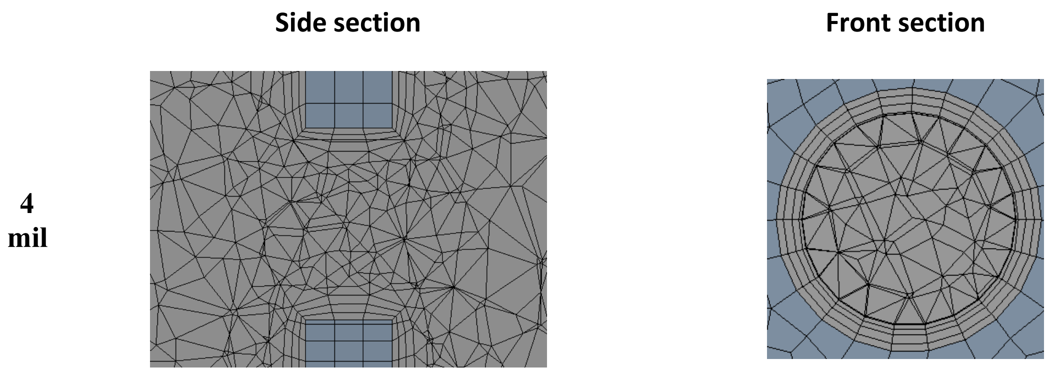


Figure 2. The geometry consists of a longitudinal slice of the unglazed transpired solar collector with the following dimensions: 2000mm x 20mm x 300mm. 1. Inlet. 2. Perforated plate. 3. Separation Plate. 4. Outlet.

2.2. Mesh

Six different meshes from 12 to 44 million elements have been realized using ANSYS Meshing. All meshes are focusing on the perforated absorber plate and more particularly on each circular hole where the air flow is the more complex and turbulent. The elements size has been set between 1 and 2mm depending on the mesh size and the maximum size is 50mm for all meshes. Because the size of the collector is large compared to the size of the holes, we had to configure a growth rate greater than the recommended value of 1.2 thus the growth rate value varies between 1.2 and 1.5 in order to reduce the number of elements. The “capture proximity” option of ANSYS meshing was activate, this option was very effective to provide a good appearance mesh in the circular hole area. For all meshes an inflation on the perforated absorber plate of 5 layers with a growth rate of 1.1 has been set. Apart from the 4 million elements meshes all meshes have been configured with a body sizing to control the mesh refinement on the perforated absorber plate. The body sizing control was set with an element size of 0.5mm and a growth rate of 1.4. The mesh with 4 million elements has not been configured with the body sizing option in order to reduce the number of elements. ***Figure 3*** presents the mesh region around the circular holes of the absorber plate for the lowest and the finest meshes, 4 and 38 million elements respectively. We can observe that even for the lowest mesh size the quality of the mesh is still good. This is due to the proximity advanced size function of ANSYS Meshing that enable sufficient refinement within the holes gap in order to capture the correct shape and characteristic of the fluid domain. Additionally, we have tried the curvature advanced size function during the mesh elaboration, but it was not relevant, thus the curvature advanced size function has not been activated.



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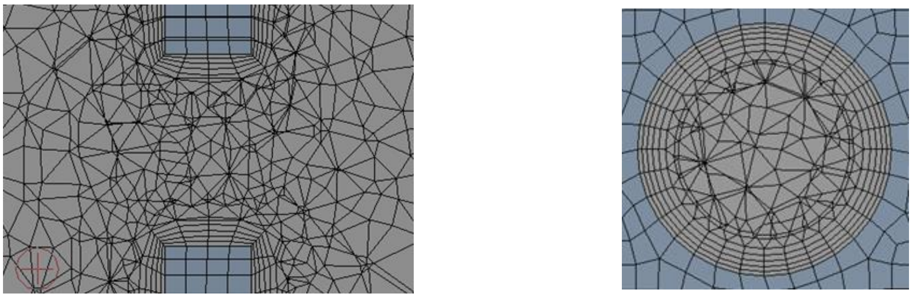

Figure 3: Mesh region around the circular holes of the absorber plate

2.3. Boundary conditions

A steady-state condition together with a pressure-based solver has been used for the CFD simulations. Regarding the turbulence model, for UTSC, RNG k-ε turbulence model seems to be a reliable turbulence model [15, 16] to be used for a correct representation of the jets free flow. Therefore, we used the RNG k-ε turbulence model for our numerical study. In addition, the Enhanced Wall Treatment has been activated, this near-wall modelling technique improve results of the RNG k-ε turbulence model near the walls [15].
The boundary conditions for the air inlet and outlet have been configured as pressure-inlet and mass-flow outlet. The air inlet temperature has been set at 25°C and the absorber plate was set as constant temperature at 55°C. Regarding the suction, a mass flow rate equivalent to 400 m3/h has been set. These values are obtained from experimental measurements carried out on this model of absorber plate [17].

3. Results

3.1. Approaches

Two approaches have been used for the analysis of the numerical results obtained by CFD simulation. The first approach is an image-based analysis that consists in an examination of the details of physical variables such the temperature and velocity magnitude for a surface/plane to finally determine the level of precision of a CFD model. In our study, we investigate the level of precision of a CFD model for different size of mesh.
In addition to an image-based analysis, an analysis of parameters such as speed and temperature was carried out for different lines to investigate more finely the influence of the mesh size. **Figure 4** present an isometric view the UTSC's slice with the three lines from which the data has been extracted. Lines 1 and 2 are used to precisely examine the influence of the mesh size through one circular hole. While line 3 help us to examine the evolution of air jets at a distance of 3 equivalent diameters (around 15mm) behind the absorber plate.

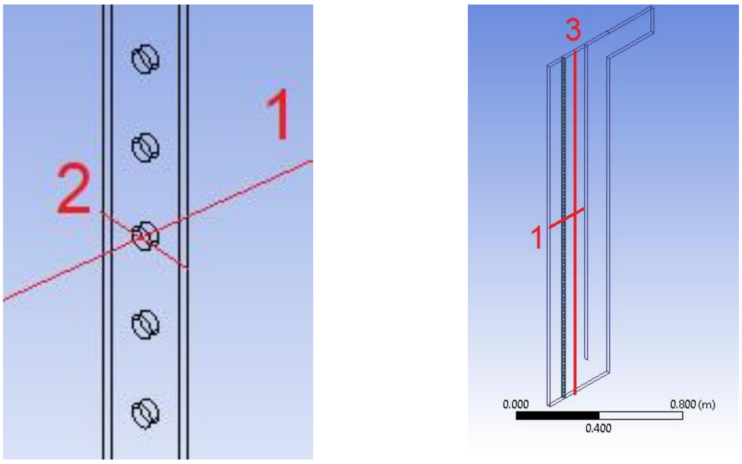

Figure 4. Isometric view of the UTSC 3D slice with the 3 analyzed lines used for results extraction

3.2. Image-based analysis

The analysis of the numerical results has been done by comparison of different velocity and temperature profiles. The accuracy of a mesh is determined in relation to the similitude with the finest mesh, composed of 38 million elements. Seven meshes have been simulated, but only the results of 6 of them are presented, 4, 7, 12, 18, 29 and 38 million elements. We chose not to present the results for the 32.5 million elements because it does not present any visible difference with the 29's million elements mesh in the image-based analysis.

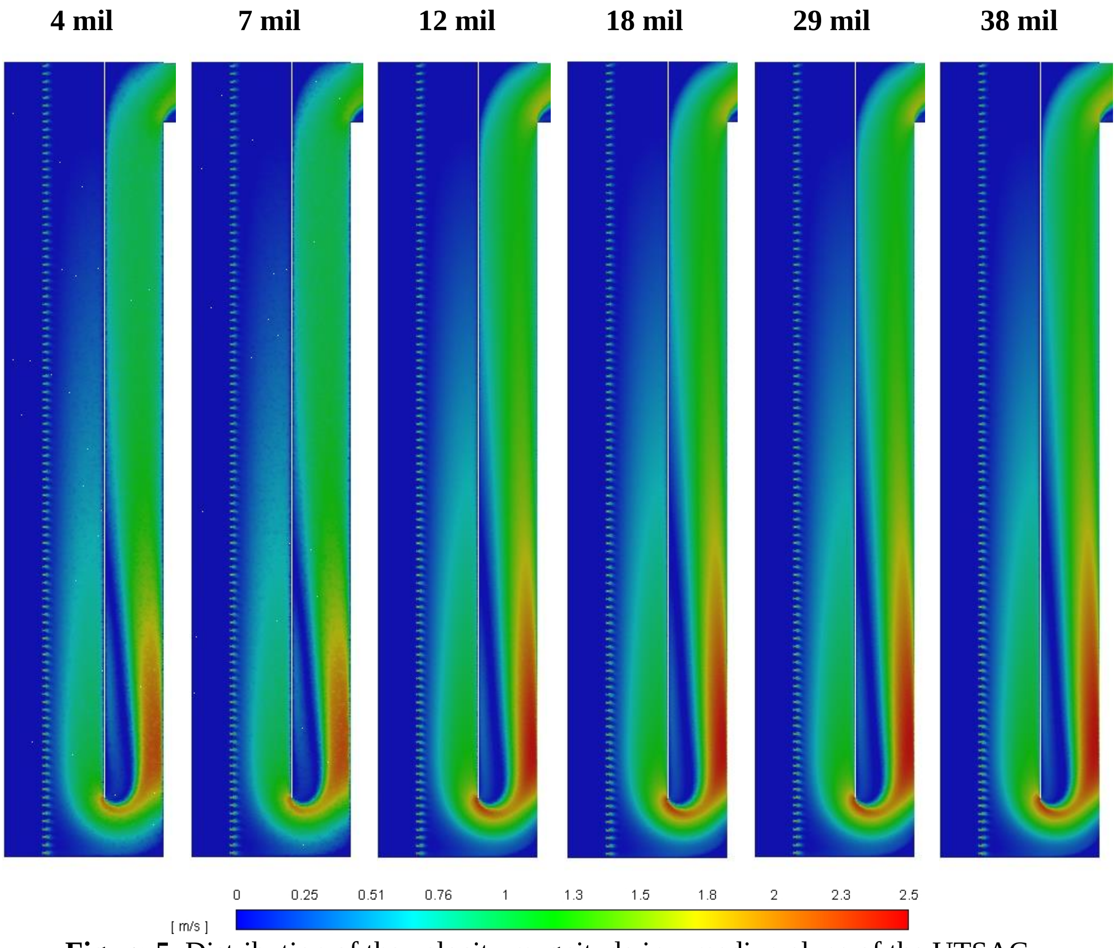

Figure 5. Distribution of the velocity magnitude in a median plane of the UTSAC.

Figure 5 show the distribution of the velocity magnitude in a median plane of the UTSAC. We can observe the mesh influence on the velocity profile on the bottom part of the UTSAC behind the separation plate. Indeed, the two coarsest meshes, 4 and 7 million elements respectively, are not able to correctly predict the velocity profile. It may be noted that the two medium meshes of 18 and 29 million elements can predict the results as well as the finest mesh.

Figure 6 and ***Figure 7*** present the velocity magnitude and temperature profiles in a median plane through two circular holes of the absorber perforated plate. These two holes are located in the lower part of the collector where the velocity and temperature profiles are more complex and turbulent than in the upper part. We may note that more the mesh is fine more we are able to predict well the evolution of the air jet thought one hole. Coarsest meshes reduce the amplitude of the air jet. Nonetheless, we do not observe a major difference regarding the prediction of the air jet thought perforated plate for the 7 meshes. This is due to the fact that in the perforated regions the mesh is sufficiently fine as mentioned in the part *2.2*.

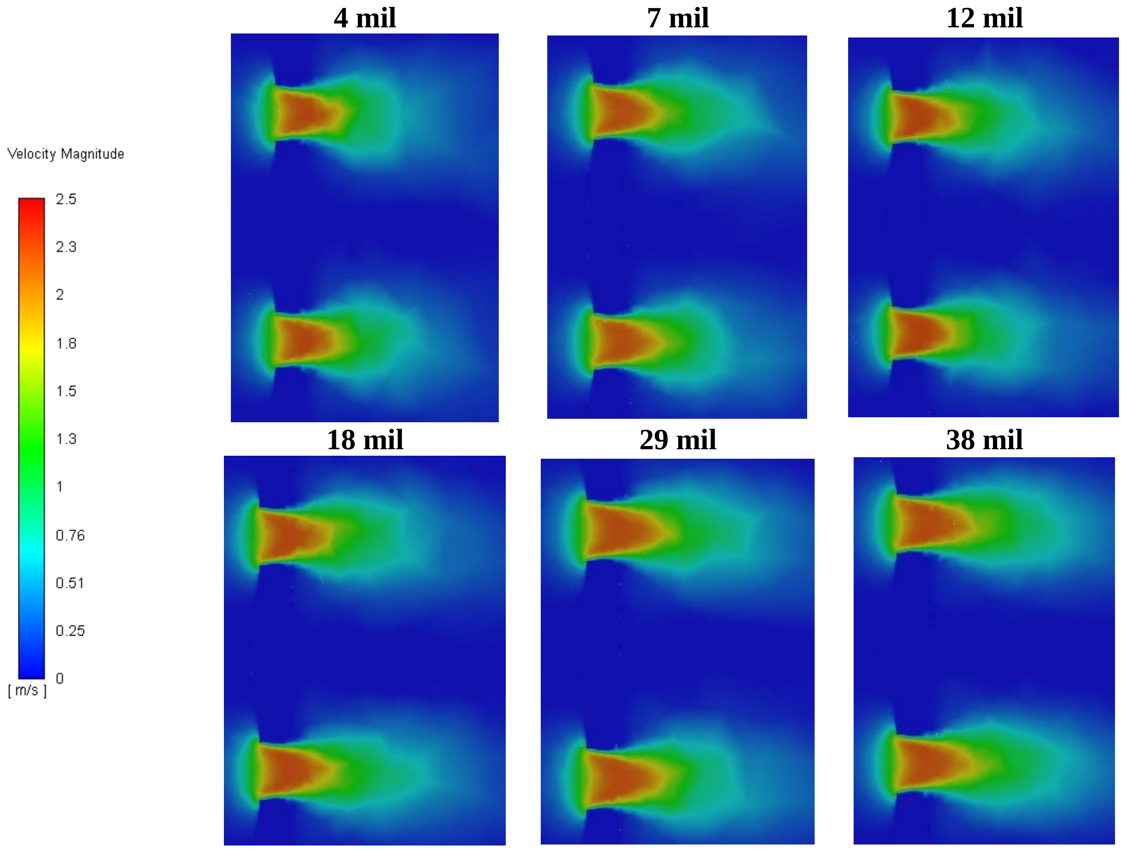

Figure 6. Distribution of the velocity magnitude through two circular holes of the absorber perforated plate.

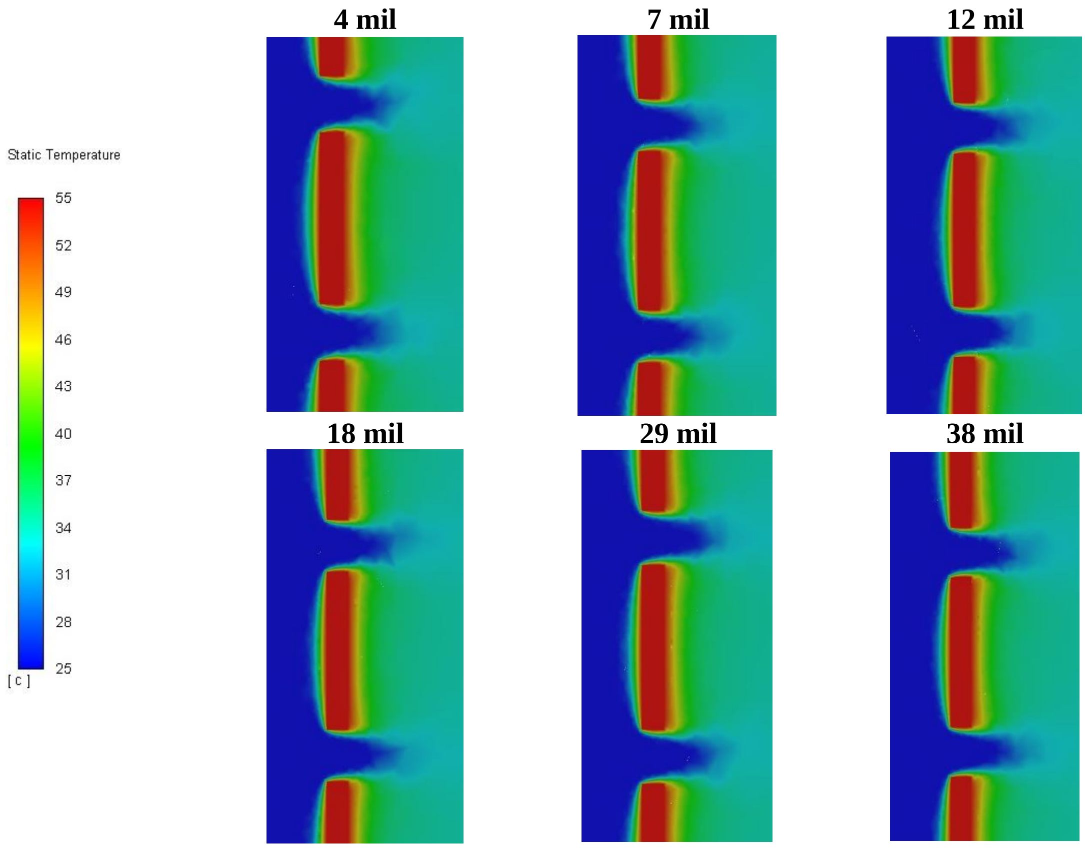

Figure 7. Distribution of the temperature through two circular holes of the absorber perforated plate.

3.3. Value analysis

Complementarily to the image-based analysis, we have carried out a qualitative study of each mesh regarding the evolution of the numerical values obtained for three axes presented in the **Figure *4***. This kind of analysis provides a finer examination of the temperature and velocity profiles, and thus to be able to capture slight variations when comparing different cases. Only cases where differences were observed are presented below.

In the ***Figure 8*** it can be observed that the meshes of 4 and 7 million elements are not able to predict the right velocities at the beginning of the curves, which corresponds to the air gap between the separation wall and the perforated plate. A similar situation is observable between 1.765 and 1.785m, at the entrance in the hole gap which is in accordance with the slight differences observed previously in the image-based analysis. ***Figure 9*** reports a similar deviation of the velocity through the hole -for the line X2, perpendicular to X1- for the two coarsest meshes of 4 and 7 million elements.

Figure 10 and ***Figure 11*** present the velocity and temperature profiles for the line X3, at a distance of 3 equivalent diameter behind the perforated plate. We may note that the meshes of 4 and 7 million elements are not able to predict neither the temperature nor the velocity near the absorber plate as precisely as the other meshes, with an error of about 20% for the velocity prediction.

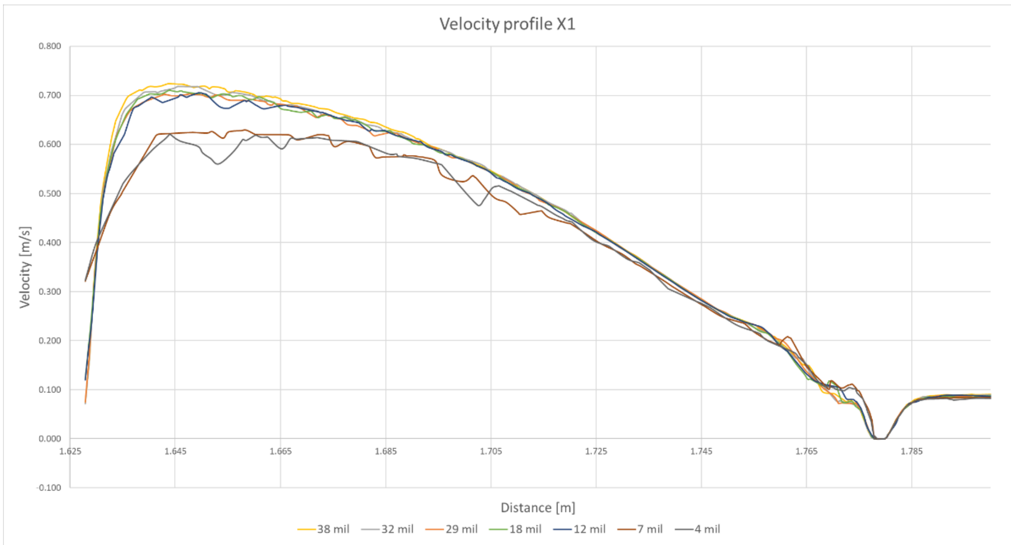

Figure 8. Velocity profile for line X1.

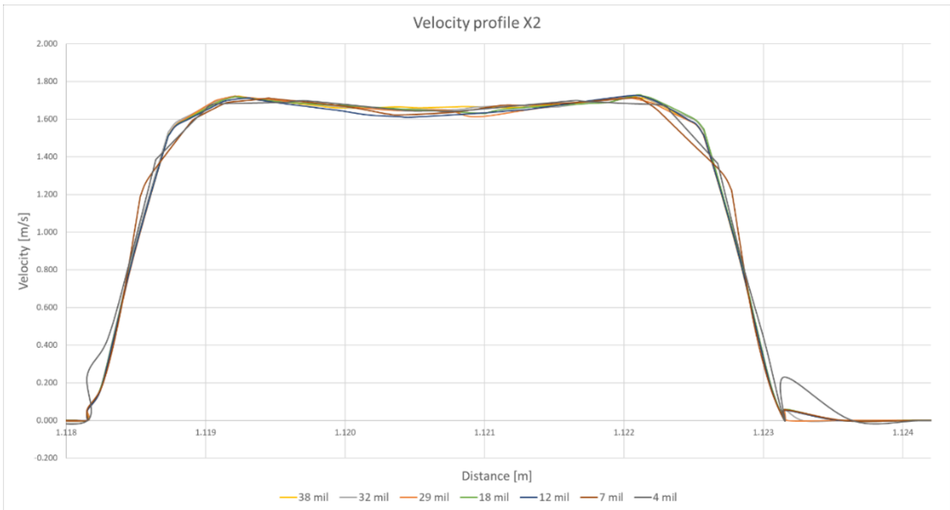

Figure 9. Velocity profile for line X2.

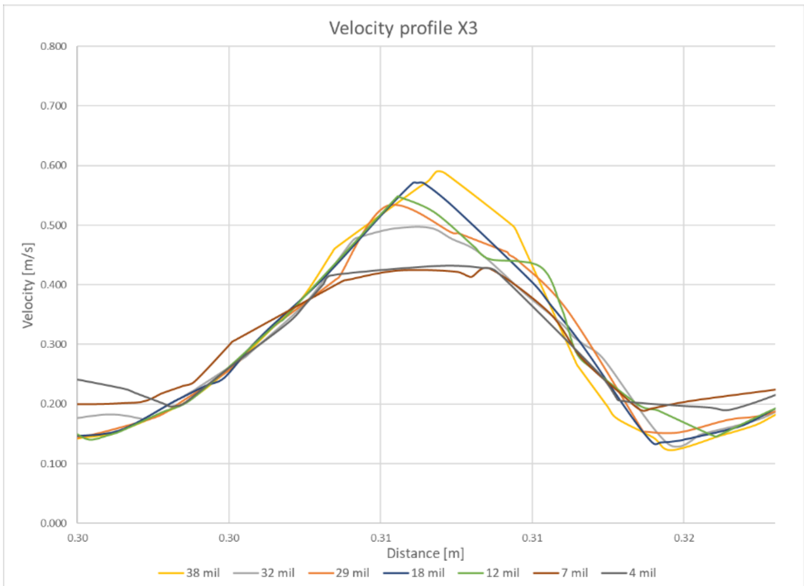

Figure 10. Velocity profile for line X3.

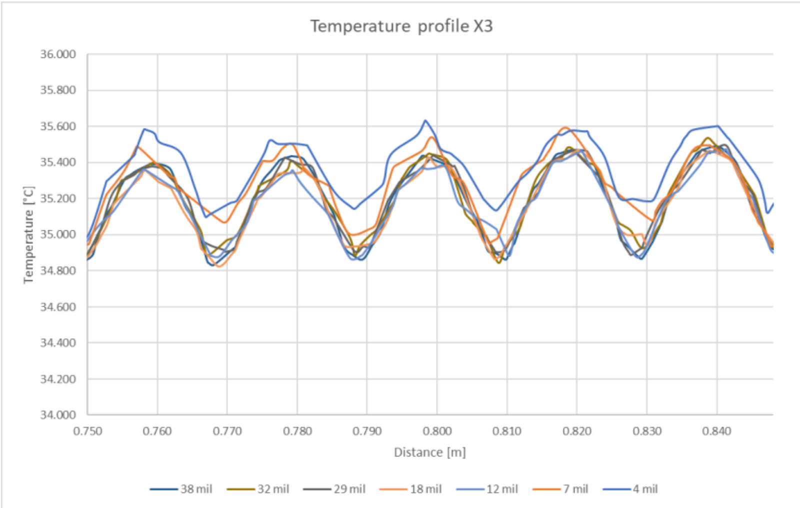

Figure 11. Temperature profile for line X3.

4. Conclusion

This study has shown the importance of the mesh size and refinement in order to capture the thermal and flow characteristics inside unglazed transpired solar air collectors.
However, it is to highlight that even with the lowest size of mesh the outlet temperature and temperature variation inside the UTSC is despite everything close to the finest mesh. Thus, for global analysis of a simple UTSC a coarse mesh could be sufficient.
Results have shown that the mesh size do not significantly influence the outlet temperature however it has an influence on the temperature and velocity profile behind the perforated absorber plate.
This must be considered for studies aiming for optimizations such as the integration of phase change materials behind the absorber plate or a second absorber plate to capture the solar radiation passing through the holes. Some optimizations provide only a small energy efficiency improvement then it is necessary to correctly predict the heat and mass transfer in the fluid domain. In our future works integration of phase change materials inside our prototype of UTSC will be studied along with the influence of the second absorber plate behind the perforated plate. Therefore, a finest mesh enabling an accurate prediction of the air flow characteristics behind the perforated absorber plate is necessary.

5. Acknowledgment

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