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INNOVATION IN VENTILATED TILED ROOFS: THE HEROTILE EUROPEAN PROJECT

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ABSTRACT: In ventilated roofs, the so-called Above Sheathing Ventilation (ASV) helps dissipating the excess heat in summer, thus reducing the cooling energy requirement. The ASV can be enhanced by increasing the air permeability of the tiled covering through the development of new tile shapes. This is the purpose of the Life HEROTILE European project, of which this work presents the preliminary analysis. The air permeability of a novel Marsigliese tile is analysed in comparison with the standard tile. The new design is improved with a higher sidelock and a new headlock pattern. A CFD model is then used to simulate the airflow through the tiles, solving the steady-state, incompressible fluid flow, in a 3D domain by means of the RANS-based standard k- ϵ model. A parametric study is conducted to analyse the variation in the air flow passing through the tile for different speeds and directions of the incident wind. The reference and new tile designs are compared in terms of air pressure drop and volumetric flow rate through tiles. The novel shape increases the air permeability up to 100%; contrary to the standard shape, the new design allows also an increase of the air flow rate as the wind blows sideways.

Keywords: ventilated pitched roof, roof tile, CFD

1 INTRODUCTION

Reducing building cooling consumption and increasing standards of indoor thermal comfort are issues of great relevance, according to the recent European environmental policies. The common strategies for improving the thermal performance of the building envelope can be summarized in increasing thermal insulation, thermal mass, solar reflectance of the roofs. Other strategies are also available, such as the exploitation of natural and forced convection by adding a ventilated layer below the roof covering.

The roof can play an important role in reducing energy requirement for space cooling in air-conditioning when compared to other building elements, due to its extension and exposure to the sun. The topic is relevant mainly in hot climates regions such as the Mediterranean area, since the energy demand for air-conditioning in summer represents a significant financial and environmental cost.

In ventilated roofs, the arrangement of battens and counter-battens supporting the tiles allows an air flow below the covering. This feature is usually recognised as the Above Sheathing Ventilation (ASV) where air flows from eaves sections (which act as an intake vent) to the ridge, helping to dissipate the excess heat in summer. Moreover, the ASV in tiled roofs is enhanced by the air permeability between the tiles, which is an additional and diffuse intake/exhaust system, as shown in Fig. 1.

Several studies have demonstrated that the performance of ASV in reducing solar heat gain. A correlation between solar radiation and ventilation rate, based on experimental data, was discussed in [1]. Full-scale models were prepared to run outdoor tests in [2, 3]. In [2], the summer performance of the ASV in combination with a radiant barrier were analysed. A significant daytime performance improvement over a standard ventilated roof was recognized.

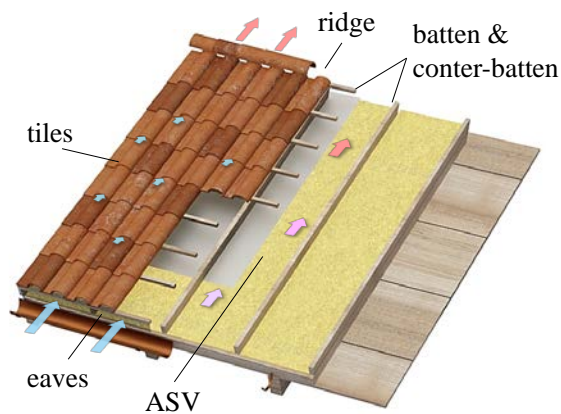


Figure 1: The ventilated tiled pitched roof

Different sizes of the ventilation duct are compared in [3]. Laboratory tests are carried out to evaluate the airflow and the temperature distribution in an ASV, as a function of the intensity of the solar radiation and the size and shape of the channel [4].

Other works used numerical models to analyse the mutual relations between air-flows and heat-transfer in ventilated roofs. A steady state numerical analysis was carried out in [5] to simulate the air flow within the small-sized-thickness duct in ventilated and micro-ventilated roofs. In the model, the tiled covering was simplified to a continuous element. A numerical model was developed and validated against experimental data in [6]. Simulations showed that the air flow induced by the buoyancy forces within the ventilated space can reduce the heat flux into the attic by 30% compared to a direct-nailed roof. Simulations were used to quantify the thermal benefits of a tiled roof over a traditional shingle roof in [7], when assuming a steady air flow, and time dependent heat and moisture levels; the estimated benefit is about 14%. In [8], the thermal behaviour of ventilated roofs was modelled with FLUENT, showing that the heat fluxes can be reduced up to 50% during summer with ventilated roofs. The effect of the air-permeability between the tiles was numerically investigated with COMSOL Multiphysics in [9]. The mass flow rate along the ventilation channel was found to be higher in the permeable ventilated roof than in the impermeable one.

In view of this, the ASV can be further enhanced by increasing the air permeability between the overlapping tiles, which is the purpose of the European project HEROTILE. The results of the preparatory action of the project are here presented. The air permeability of a standard roof

tile is numerically analysed and compared with a novel tile shape, which is specifically designed to improve the ASV effect. A parametric study is conducted to analyse the variation in the air flow passing through the tile, according to different velocities and directions of the incident wind.

2 THE HEROTILE EUROPEAN PROJECT

The LIFE HEROTILE is a European research project (Life programme, contract number LIFE14 CCA/IT/000939) that will facilitate the implementation of energy savings strategies in the building sector. The project involves industrial, academic and public partners, from several countries: Italy, France, Germany, Spain and Israel. The project will address climate change mitigation policies with technologies and systems suitable for being replicated, transferred and disseminated.

The preparatory action of the project has been focused on the tile shape optimization to obtain a high air permeability through the overlap of the tiles, and consequently to increase the air flow rate in ventilated roofs. Over 20 new shapes of two traditional roof tiles (Portoghese and Marsigliese tiles) were designed.

Firstly, a comparative analysis of the permeability to air of new tile designs was carried out by means of a CFD code. The model was calibrated using an experimental rig, where the performance of existing tiles were measured and used as the benchmark [10]. Secondly, the three best performing tiles for each type (Portoghese and Marsigliese) were selected for prototyping and testing in a wind tunnel to check their permeability to water. Finally, a Portoghese and a Marsigliese, that proved to be the more effective, were produced and they are now under testing on two real scale mock-up of a tiled pitched roof, located in Italy (Ferrara) and Israel (Yeruham), respectively. In order to evaluate the performance of a pitched roof equipped with the new tile shapes in comparison with other roof typologies (e.g. traditional roof tiles covering, metal covering, flat roof), each mock-up consist of several rooms as shown in Fig. 2 and 3, all of them equipped with anemometers, heat flux meters, and temperature sensors for a comprehensive monitoring.

The final stage of the project will be focused on the implementation of two pilot plant for tiles production and the testing of the new tiles in real buildings.

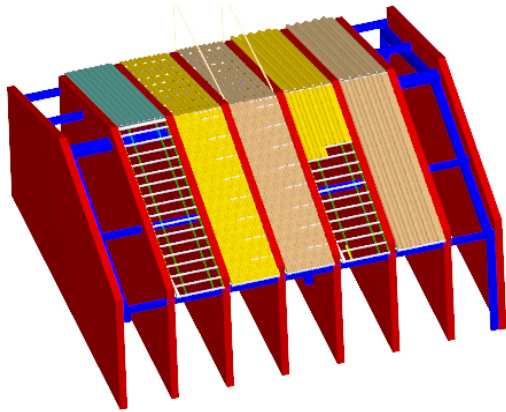


Figure 2: The mock-up concept



Figure 3: The mock-up in Ferrara, Italy

3 METHODOLOGY

The purpose of this preliminary analysis of the permeability to air of new roof tiles designs was to provide an aid to the design process itself and an evaluation criteria for the preparatory action of the HEROTILE project. As a part of this effort, in this study we analyse the behaviour of a standard Marsigliese roof tile in comparison with the best performing new shape (in the following STD and NEW, respectively), which are shown in Fig. 4. The NEW tile design involves a sidelock modification (red highlighted in Fig. 4), which is higher than in the STD type. Moreover, since the labyrinthine path formed by the gap between tiles (required to prevent the driving rain to enter), had a very small cross-section, a new headlock pattern has been modified to yield a lower pressure drop, whilst retaining the driving rain function.

In order to analyse the potential benefits of the new shape in terms of its permeability to air, the CFD Module of COMSOL Multiphysics (based on FEM method) is used to carry out a parametric study of the variation in the air flow passing through the tile, according to different wind speed and direction. The STD and the NEW are compared in terms of air pressure drop and volumetric flow rate through tiles.

3.1 Numerical model

The finite-element code COMSOL Multiphysics V5.2 is used to solve the three dimensional, incompressible fluid flow in steady state. The RANS-based standard $k-\epsilon$ turbulence model is applied. The STD and NEW Marseillaise tile shape have been imported in COMSOL Multiphysics from CAD drawings by means of the CAD Import Module.

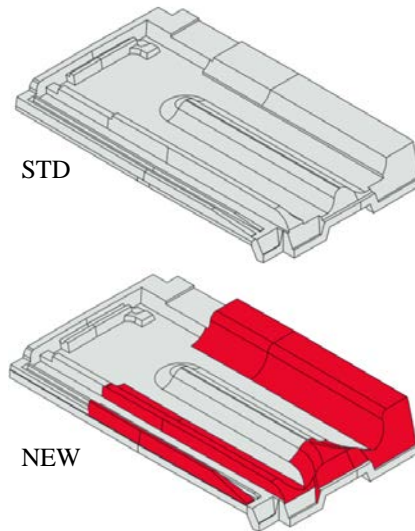


Figure 4: Marseillaise roof tiles

Each 3D tile model was subjected to a pre-processing phase in order to remove unnecessary details and surfaces features that could lead to a problematic control of the meshing process.

Preliminary air permeability tests were carried out with a dedicated experimental setup. The pressure difference across a layer of standard Marsigliese tiles (taken as the reference) was measured at given air flow rates. The results of air permeability tests have been used as the benchmark to calibrate the CFD model, which replicates experimental setup. In order to model the distortion of individual real clay tiles (due to the drying and firing processes) with the regular CAD geometry, the spacing between the overlapping tiles was considered as a calibration parameter. More details about the testing activity, the calibration of the CFD model and the air permeability numerical analysis of the new tile designs are presented in [10].

In the numerical model, the two 3D domains replicate the geometry of the rig, in terms of plenum and placement of the tiles, as shown in Fig 5. The upper box was introduced to set the boundary conditions simulating the wind field occurring over the tiles; its size was chosen to limit the number of finite elements and the impact on the local flow field between tiles. The air flows from the upper volume to the lower one through a section which

consists of the equivalent overlapping of four tiles (equivalent to the 2x2 tile section left unsealed in the test rig). A detail of the tile section (n°3 in Fig. 5) is shown in Fig. 6.

Different boundary conditions have been set to account for the modelling of the different wind directions and intensities. Six boundary surfaces of the upper air volume are set as open boundary conditions and the wind velocity was imposed on the remaining three boundaries, showed in red in Fig 5. This arrangement was chosen because the wind only blows from one side with different angles and intensities. All other surfaces were defined as no-slip walls (preparatory models showed surface roughness effects to be negligible).

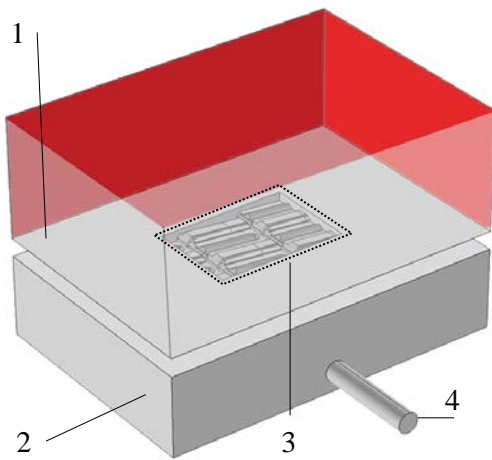


Figure 5: 3D model domain (1:upper air volume; 2: bottom air volume; 3:tiles section; 4:outlet)

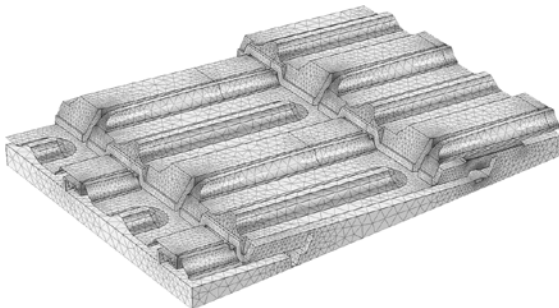


Figure 6: Detail of tiles section and of the mesh

Finally, the air flows out from the exhaust tube at the bottom, whose outlet section is set as open boundary condition.

Different mesh resolutions (extremely coarser, extra coarser, coarser and coarse, which results in 680 000, 730 000, 920 000, and 1 600 000 elements, respectively) have been tested in order to

produce reliable and mesh-independent results for both STD and NEW. The coarser mesh, which is

shown in detail in Fig. 6 for the tiles section, was considered an acceptable compromise between mesh resolution and time required for simulations.

4 PARAMETRIC ANALYSIS

The air flowing through the tiles is influenced by the action of the wind over the roof structure and the tile shape. To investigate this effect, a detailed parametric analysis is carried out with regard to the wind conditions. The STD and the NEW shapes are analysed simulating 30 different wind conditions: three wind speeds ($i = 1.0, 2.0, 5.0\text{m/s}$) blowing over the tiles, five horizontal wind directions ($\alpha = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ$), two vertical inclinations ($\beta = 20^\circ, 30^\circ$) which accounts for equivalent pitched roof slopes, as shown in Fig. 7.

4.1 Results

In Fig. 8 and 9, the air flow rate in STD and NEW cases is shown for a roof slope of 20° (β) and 30° , respectively, according to the wind angle of incidence (α), and the wind intensity, i .

The NEW shape always has higher air flow rates than the STD shape. This can be mainly attributed to the modified geometry of the sidelock in the

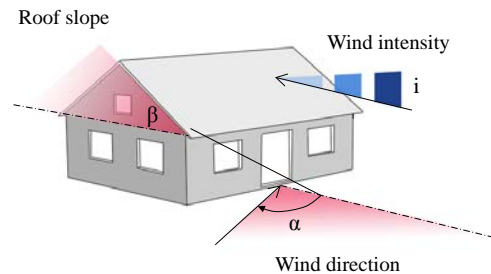


Figure 7: Study parameterization

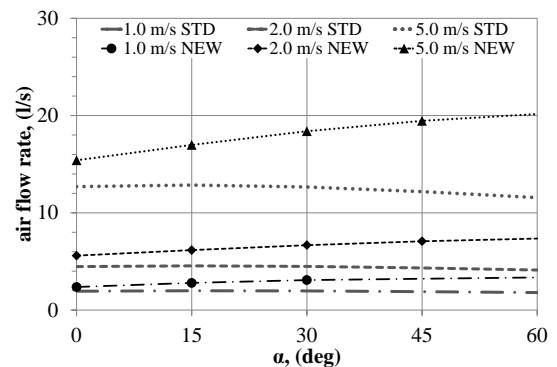


Figure 8: Air permeability and wind direction: roof slope 20°

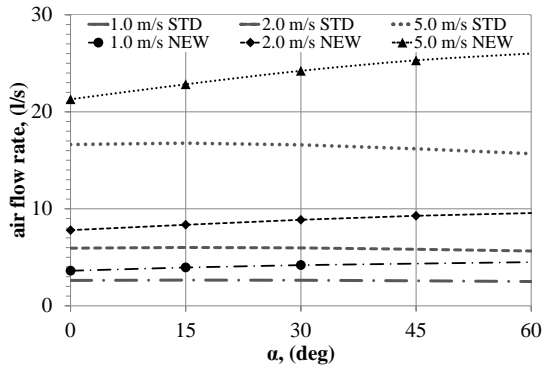


Figure 9: Air permeability and wind direction: roof slope 30°

NEW shape, which act as intake vent allowing more air flow in through the side of the tile.

As the incident wind horizontal angle (α), changes from 0° (facing the tiles head-on) to 60° (around the side-on) a decrease in the air flow rate is observed in STD as expected; on the contrary the air flow rate increases as the wind direction moves to the lateral opening of sidelock in the NEW case. The increase in the air flow rate is over the 60% at 45° wind angle and 20° roof slope for all wind intensities simulated.

The fluid flow stream lines through the tiles are shown in Fig. 10, for the NEW shape with $\alpha = 45^\circ$, $\beta = 20^\circ$ and $i = 2\text{m/s}$. The NEW Marsigliese shape produced a significant improvement in the air permeability.

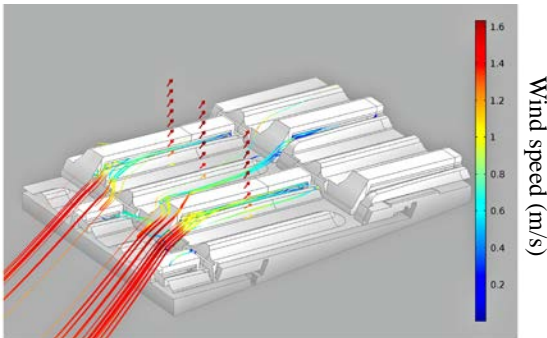


Figure 10: Air-flow stream lines through the tiles (NEW, $\alpha = 45^\circ$, $\beta = 20^\circ$, $i = 2\text{m/s}$)

The NEW sidelock, modified in height and geometry to have a larger opening, is exposed to the wind when it is blowing sideways and therefore, the airflow path is diverted towards the ASV.

In Fig. 11 and 12, the air flow rate in the STD and NEW is shown for a roof slope of 20° (β) and 30°, according to the pressure difference between an internal and external point probe. The pressure is measure internally at the bottom corner of the plenum; the external pressure is measured in central position at the top of the domain (upper air volume). In the figures, the three cases related to different wind intensity, and five cases related to the

different wind direction are shown. The STD case and the NEW shapes diverge in clockwise and anticlockwise directions, respectively, although both cases shows similar values at 0° incident wind horizontal angle. This confirms the increasing air flow rate with wind direction in the NEW shape, which was earlier observed.

5 SUMMARY AND CONCLUSIONS

This work presents a part of the results obtained from the analysis of the air permeability of tiles, which was carried out during the preparatory action of the LIFE HEROTILE European project.

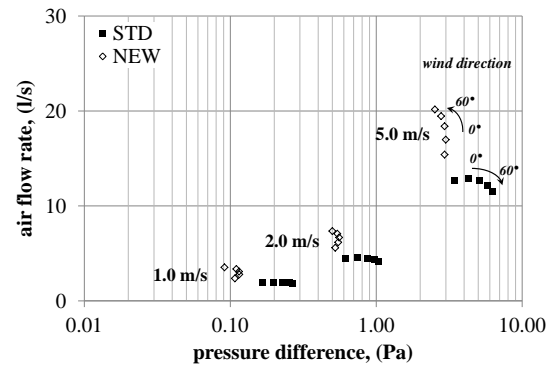


Figure 11: Air permeability and pressure difference: roof slope 20°

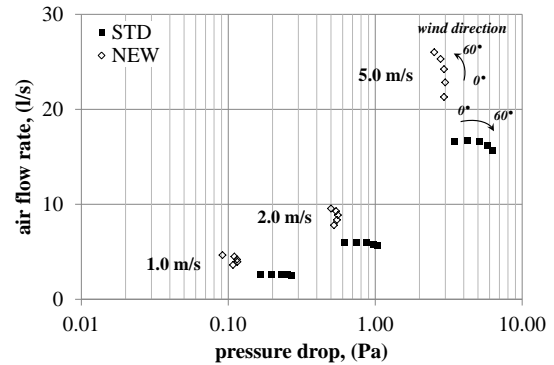


Figure 12: Air permeability and pressure difference: roof slope 30°

The objective of this preliminary analysis was to provide an aid to the design process of innovative tile shapes to obtain an increase in the air flow rate through the tiles and consequently to enhance the effectiveness of the ASV in reducing the heat transfer between the tiles and the roof structure.

The permeability to air of a novel shape of Marsigliese tile is analysed in comparison with the widespread tile shape on the market, which is taken as the reference one. The innovative tile has been modified in the sidelock, which is higher than in the standard, and in the headlock pattern to yield a lower pressure drop, maintaining the driving rain

function.

The analysis is carried out numerically, by using the CFD module of COMSOL Multiphysics to simulate the airflow through the tiles, solving the steady-state, incompressible, turbulent fluid dynamic problem in a three dimensional domain by means of the RANS-based standard k- ϵ model. The numerical domain replicates the geometry of an experimental rig, which was used to test the performance of existing tiles. The measurements from the test rig were used as benchmark to calibrate the 3D CFD models.

The CFD models are used to carry out a parametric study of the variation in the air flow passing through the tile, according to different wind speed and direction. The standard and the new tile shapes are compared in terms of air pressure drop and volumetric flow rate through tiles. Overall, 30 wind condition scenarios have been simulated, combining four different wind speeds, three roof slopes and six horizontal wind directions.

The novel shape of the tile allows a significant increase in the air permeability up to 100% in comparison to the standard tile. Moreover, the new design of the sidelock produces an increase in the air flow rate through the tiles when the wind direction moves from directly up the roof slope coming in from the side. This effect is evident at both roof slopes and wind speeds modelled.

6 ACKNOWLEDGMENTS

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