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Numerical Simulation of Thermal and Fluid Dynamic Phenomena as a Tool for Energy Eficiency in Buildigs. Application to Refrofiting Edification.

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Abstract

The present paper shows the work carried out by the authors in the FP7 EU project "Retrofitting solutions and services for the enhancement of Energy Efficiency in Public Edification (RESSEEPE)". Different numerical simulation tools for the thermal and fluid dynamic behavior analysis of different technologies for retrofitting solutions have been developed and adapted. These technologies, which are being implemented in four European public buildings, have been numerically analyzed in order to have a better understanding of their behavior and virtually analyze their energy efficiency for optimization purposes. Aerogel-based super insulating mortars have been analyzed with the objective of obtaining the optimum size of aerogel mixed with the mortar that provides a lower thermal conductivity. Effects of envelope and thermal bridges on vacuum insulating panels have been studied to analyze their influence on effective thermal conductivity. PV panels coupled with ventilated façades have been studied in order to obtain the optimum gap of the ventilated façade depending on working and climate conditions. Finally, new flat plate solar collectors have been optimized by means of different numerical simulation tools obtaining a high efficiency thermal collector for a wide range of working conditions. These different technical solutions have not only been numerically analyzed for optimization purposes but also have been employed as retrofitting solutions in four different real public buildings under their specific climate conditions. Numerical methodologies, obtained numerical results, different experimental comparisons and expected energy reduction are analyzed, presented and concluded.

Keywords – numerical modeling; energy efficiency in buildings; retrofitting solutions; insulating materials; PV panels; ventilated façades; solar collectors.

1. Introduction

Although the energy consumption in Europe is expected to rise only moderately in the next 20 years, the Energy Efficiency Buildings European Initiative has the objective to mitigate this problem aiming a reduction of 165 million tons of emissions (Mtoe) from the existing buildings (in 2005) and a contribution of 50 Mtoe from renewable energies during the period from now until 2020. Existing public buildings have a huge impact on the total energy consumption in Europe. The potential for energy savings is thus particularly important at national and European levels, where many facilities are very energy-intensive, and where the priorities are the functional quality of the buildings and the respect of optimal use conditions.

Within the framework of the FP7 EU project "Retrofitting solutions and services for the enhancement of Energy Efficiency in Public Edification (RESSEEPE)" [1] different technologies have been analyzed in deep: i) Insulation strategies for energy conservation have been focussed on innovative ideas like aerogel-based superinsulating mortars or the use of very efficient vacuum insulating panels (VIP), ii) Solar strategies for energy and heat recovery have been oriented to electrochromic windows, photovoltaic panels coupled with ventilated façades or innovative high efficiency flat plate solar collectors, iii) Strategies for thermal energy storage have been adapted from sensible/latent heat thermal energy storage to seasonal thermal energy storage, iv) Lighting strategies based on LED solutions, v) Strategies for efficient HVAC systems from dimensioning and control strategies to predictive models, vi) Possible Combining technologies. Four of these technologies described above have been numerically studied for optimization purposes in order to know the optimal values or the better efficieny on: aerogel superinsulating mortar; the influence of thermal bridges on VIP panels; the optimum air chanel gap between an external PV panel and an internal insulated wall; and the new high efficient design of a flat plate solar thermal collector.

The present paper is focused on describing these four technologies, the numerical tools developed for each of them, and the results that give information not only on the thermal and fluid dynamic behavior, but also on their thermal efficiency and energy savings. All these numerical results are going to be validated under the implementation of these technologies in real demo sites from Southern Europe hospitals, Central Europe University and Northern Europe School.

2. Insulation strategies

Two different superinsulation technologies have been investigated: aerogel-based materials [2] and vacuum insulating panels [3]. For the first case, a numerical simulation model of the thermal conductivity in a 3D test probe of aerogel-based superinsulating mortar has been developed with the objective of numerically obtaining the equivalent thermal conductivity of the final product as a function of percentage of aerogel volume and for a range of possible sizes of aerogel inside the mortar. For the second case, a numerical simulation model of the equivalent thermal conductivity of different VIPs joined together has also been developed with the aim of studying the influence of thermal bridges on the final equivalent thermal conductivity.

2.1 Aerogel-based superinsulating mortar

A numerical model to analyze the equivalent thermal conductivity of multi-material mortars, including not only multilayer components, but also non-uniform elements like aerogel with the possibility of random sizes of sphere diameter has been developed. In that sense, the mathematical formulation, the numerical resolution, the numerical verification of the test, and the numerical results reproducing the experimental test of equivalent thermal conductivity analysis are here presented.

From a numerical point of view, the Fourier's law states that in a steady-state scenario, the conduction of heat within a solid is governed by the equation $\mathrm{q} = -\lambda \nabla \mathrm{T}$, with q the heat flux, λ the thermal conductivity, and T the temperature.

For the present study, the numerical model used discretizes the above equation on a finite-volume basis suitable for 3D unstructured, as well as Cartesian, meshes and its resolution is performed by means of high performance parallel computing. Additionally, the model is able to assign different values of λ to each control volume. Hence, the mesh cells located at the bulk of different materials will have their particular values of thermal conductivity λ_K, while for the cells in which two or more materials coexist, the average thermal conductivity will be calculated considering the amount of volume fraction of each material k, C_k, within the cell, such as $\lambda_{avg} = \sum C_K \lambda_K$.

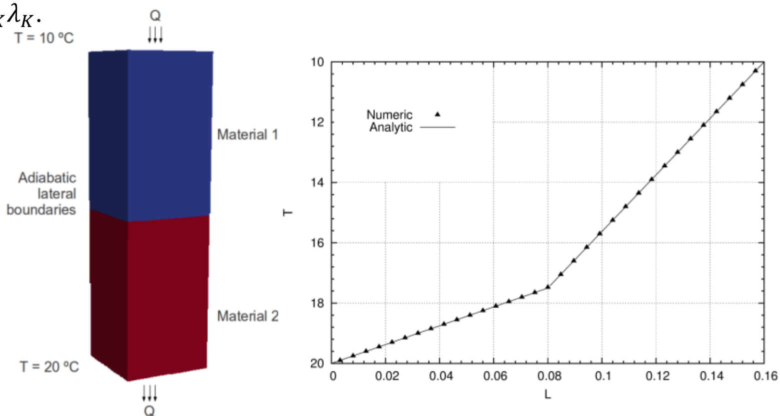


Fig. 1 Schematic drawing of the test (left). Numerical and analytic results along a centered vertical line (right).

The first step consists in the validation of the model. For this purpose, the distribution of temperatures within a rectangular sample of two different materials under a constant vertical heat flux, with given top and bottom boundary temperatures, and presenting adiabatic conditions at the laterals, see Fig.1 (left), is calculated both numerically and analytically. The numerical results are obtained by the discrete model using 100 hexahedral cells in the vertical direction, while the analytical ones are obtained directly from Fourier's heat conduction equation. The results for both cases, plotted in Fig. 1 (right), demonstrate that the numerical model is able to accurately solve heat conduction problems.

Once the model is validated, the numerical tests are performed. The study considers a rectangular sample of dimensions 80x40x20 mm, see Fig. 2, meshed by means of 729K uniform hexahedral cells. Again, a vertical constant heat flux is imposed at the top and bottom boundaries with given temperatures of 10 and 20 ºC, respectively, together with adiabatic conditions at the lateral boundaries. However, in this case, instead of having two materials separated by a plane, the two materials randomly occupy the domain: continuous phase of mortar with random spheres of aerogel. The study performs a parametric study of the averaged sample conductivity, λ, obtained from the combination of both materials: 0.02 W/mK for aerogel and a range from 0.1 to 0.06 W/mK for the mortar.

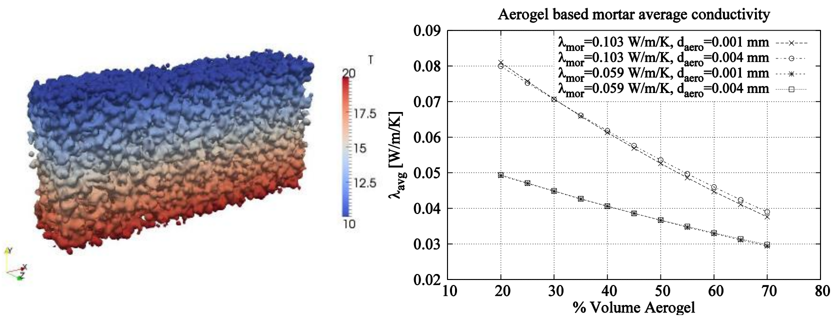


Fig. 2 Schematic drawing of the test (left). Numerical and analytic results along a centered vertical line (right).

The numerical results show that the aerogel size has no influence on thermal conductivity variation with the same percentage of volume. Thermal conductivity has a linear tendency independent from the random position of spheres.

2.2 Vacuum insulating panels

VIP panels encapsulated into thin polyurethane layer have been numerically analyzed not only characterizing the multilayer effect of the panel within the layer, but also simulating the junction effect between panels under different geometrical compositions, looking for an equivalent thermal conductivity value.

The numerical model used for the simulation of the VIP-PU (CombiPlate) elements is based on the one presented in Sec. 2.1. The numerical scheme discretizes the Fourier's heat conduction equation on a finite-volume basis suitable for 3D unstructured, as well as Cartesian, meshes and its resolution is performed by means of high performance parallel computing. Once again, the thermal conductivity is calculated by means of the approach presented in Sec. 2.1, and the validation of the model is not shown in this section, since it is similar to the one presented in the previous section.

As shown in Fig. 3, three different situations are analyzed: (a) single CombiPlate element, (b) two coupled CombiPlate elements, (c) three combined CombiPlate elements. Rectangular VIP material has dimensions of 990x590x12 mm, equidistantly surrounded by PU material such that the resulting overall element has dimensions 1000x600x20 mm. The thermal conductivity of the VIP is 0.004 W/m·K, while the PU material presents a value of 0.03 W/m·K.

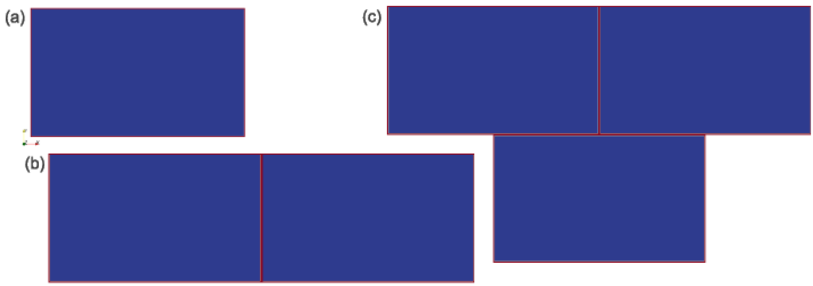


Fig. 3 Inner slice of the three cases studied: (a) one; (b) two and (c) three CombiPlates

The numerical results following the same numerical test as in Sec. 2.1, with meshes ranging between 1.5M and 3M of cells per CombiPlate give equivalent thermal conductivities of 0,0068W/mK; 0,0069W/mK and 0,0072 W/mK, respectively.

3. Renewable electrical energy

In this section a PV ventilated façade is presented. The idea of this façade is to develop a higher efficient PV panel linked to a substructure that gives a channel gap between the wall and the panel. A VIP panel is also attached to the wall to reduce the inner layer heat transfer losses (see Fig. 4).

In order to predict the optimal gap depending on structural geometry and climate conditions, a numerical model has been developed to simulate the PV panel behavior, the channel air flow through the gap, and the heat transfer through the VIP panel.

PV Panel element is modelled as an opaque one-dimensional conduction element with inner heat generation. The present work only focuses on the thermal behaviour of the PV Panel. The inner heat generation of the element is defined as the total solar energy not used in the electricity generation, i.e:

$$\dot{Q}_{PV} = (1 - \eta_{PV}) Q_s \frac{A_s}{V_{PV}} \tag{1}$$

where η_{PV} is the electrical efficiency, Q_s is the incident solar radiation, A_s is the lateral area and V_{PV} is the volume of the PV Panel. This term is then taken into account as a source term in the transient one-dimensional conduction equation.

The Vertical Channel element is vertically divided into a number of control volumes (CV), where the nodes are located in the center of the CVs. The temperature and pressure maps are evaluated in the nodes of the centered mesh, while the velocity field is evaluated at the faces of the centered CVs, which correspond to the staggered grid as shown in Fig.4. Mass conservation, momentum and energy equations are solved for one-dimensional and transient conditions following SIMPLEC algorithm. Opaque Wall element is modelled like a PV Panel element except for the inner heat generation. Further details of the governing equations and numerical models used in the present study are given in [4].

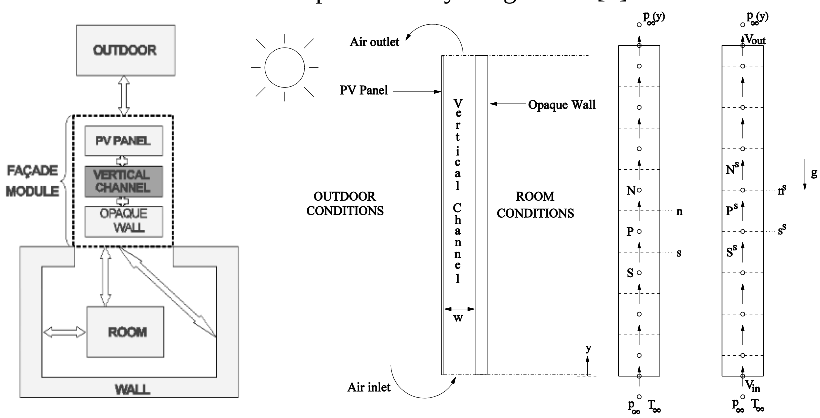


Fig. 4 System scheme as elements collection (left). Vertical channel discretization (right).

The simulations are assumed to start from an initial map of temperatures corresponding to the monthly average outdoor temperature of the demonstration site location. Fig. 5 shows characteristic meteorological conditions corresponding to Barcelona during July obtained using Meteonorm ® Software.

As an illustrative example of numerical study, different channel widths from as narrow as 0.03m up to 0.5m have been analyzed to provide the channel width that maximizes the total evacuated heat by the ventilation channel for a given period of one month for January and for July.

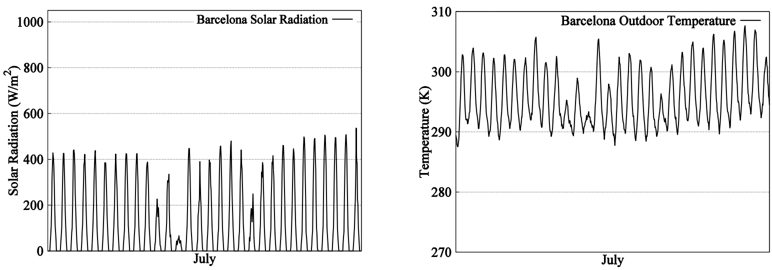


Fig. 5 Meteorological conditions from Barcelona (Spain) during July.

The analysis shows that for Barcelona in summer period, the maximum heat evacuation takes place for a channel width of w=0.17m, although the results do not deviate significantly from this value within the interval of w=0.13m-0.20m. As for the winter period, the maximum heat evacuation is obtained at w=0.10m, again without significant differences in the checked values within the interval of w=0.08m-0.12m. If the identical analysis, using the same façade configuration, is carried out for UK cities (Center Europe) and Sweden cities (North Europe), the channel thicknesses that maximize the heat dissipation in summer period are w=0.13m and w=0.17m, respectively. For winter, however, the values are found as w=0.08m for both locations.

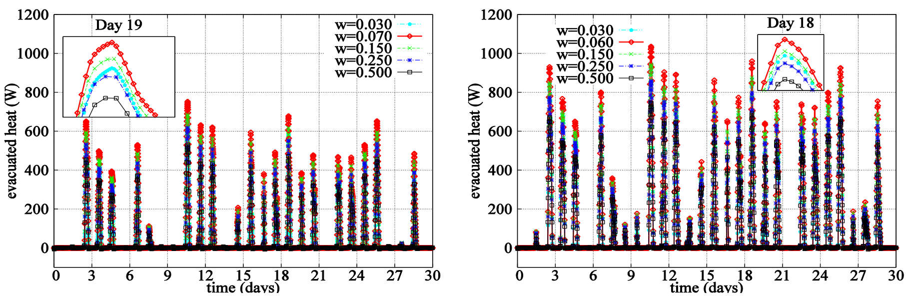


Fig. 6 Evacuated heat in July (left) and January (right) for Barcelona.

4. Renewable thermal energy

In this section, a novel solar flat plate collector is presented with the aim of increasing collector efficiency (compared with the actual conventional commercial ones, with a similar price). The basic idea of this proposal is to add a transparent insulation material (TIM) including an overheating protection system. Fig. 7 shows the collector scheme and the UPC experimental setup where the collector has been tested.

A mathematical model has been used to numerically analyze the solar flat plate collector developed by [5] within a modular object oriented platform called NEST [6], which allows the linking between the different elements to perform a specific system or configuration considering the sum of various components interacting with each other (ambient, glass cover, TIM, air gap, absorber, fluid, ventilation channel and insulation). The proposed model is based on the numerical resolution of the different elements by means of an algorithm able to use different levels of simulation, where each object in the system can communicate with the other objects to send or receive any information necessary for its resolution as shown in Fig. 8. Each element in the system is interchangeable and could be substituted by high-level CFD object [7] if needed with a possibility to parallelize the whole simulation in order to reduce the computational time.

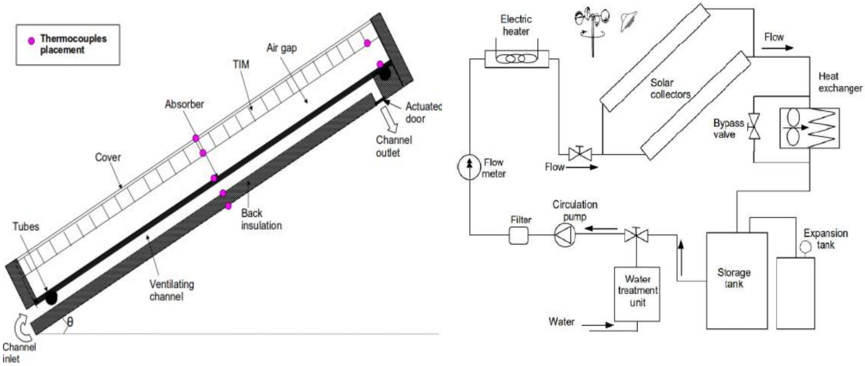


Fig. 7 Collector cross section with ventilation channel and honeycomb cover (left). Experimental setup (right).

Fig. 8 shows details of conduction, convection and radiation energy flow solved over the glass cover, within the TIM, through the air gap, absorber, fins, tubes, and inclined channel working under close or open mode.

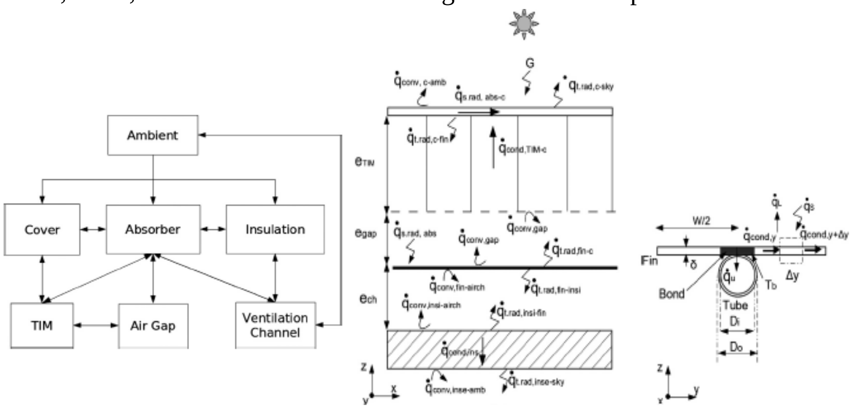


Fig. 8 Modular FPSC scheme (left). Heat fluxes collector cross section with TIM and detailed fin (right).

Detailed CDF&HT numerical simulations have been carried out for air gap TIM in close channel (Fig. 9) analyzing the periodic recirculation of the air trapped in the cells, observing that recirculation velocity magnitude is about four times smaller than that observed in the air gap, consequently reducing the heat losses from the absorber through the cover, while hot air that remains trapped in the air gap, contribute to increase the absorber temperature and thus increasing the global efficiency of the collector.

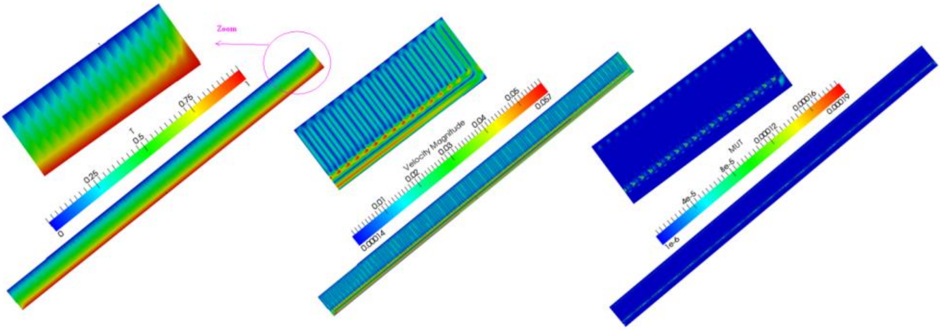


Fig. 9 Instantaneous non-dimensional temperature and velocity maps at section plane XY.

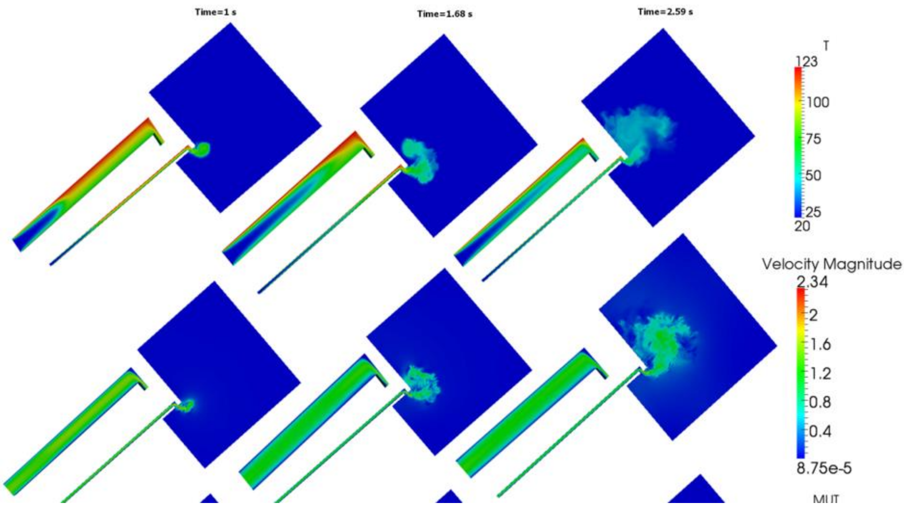
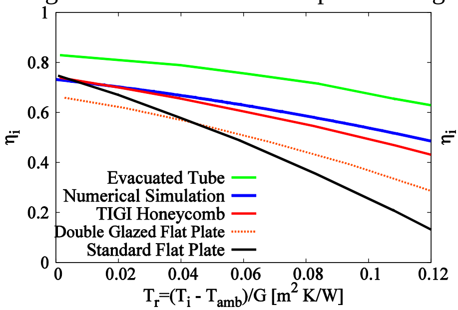


Fig. 10 Instantaneous temperature and velocity maps at section plane XY.

In a similar manner, detailed CDF&HT numerical simulations have been carried out for the same air gap + TIM in an open channel (see Fig. 10) when temperature of the channel reaches a very high temperature and thus it has to work in its open mode. In this case, the jet outgoing from the channel by natural convection is analyzed to assure that the collector is cooled to acceptable working conditions. Fig. 10 shows illustrative results of the initial transient evolution of open channel flow observing that the flow inside the channel is laminar, while the jet near the outlet of the channel is turbulent.

Finally, Fig. 11 shows the efficiency curve of the new flat plate solar collector numerically modeled (blue line, left) and experimentally tested (blue line, right) in comparison with different existing collectors, from standard one (black line) to evacuated tube (green line). Reasonable agreement on the first half part of the graphic is obtained.



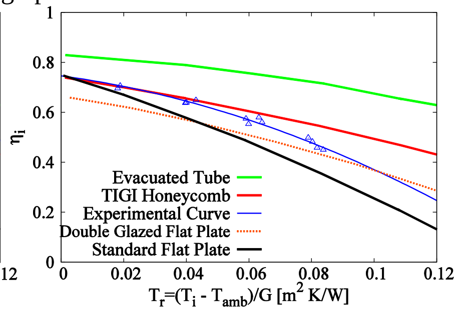


Fig. 11 Efficiency curves of different flat plate solar collectors.

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[1] European Union's Seventh Framework Programme for research, technological development and demonstration under Grant Agreement no: 609377A FP7-2013-NMP-ENV-EeB project (2013-2017).

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