Stay cool without fossil fuel. A passive eco-cooler for low-income population in informal settlements

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Abstract. With climate change severe events, more and more vulnerable populations suffer from extreme heat waves. This paper presents a hands-on experimental idea for testing vernacular passive cooling strategies using traditional Shisha clay funnels for the Egyptian hot dry climate. Several clay funnels were investigated in terms of shape, size and form. The clay funnels were measured and simulated for their efficiency in accelerating air flow inside residential units and ability to enhance the air velocity if used combined with cross ventilation strategies. Computational Fluid Dynamics (CFD) simulations were conducted in ANSYS Fluent to understand the airflow behaviour inside the simulated test shoe boxes resembling living rooms - using the standard k-ε turbulence model - for single and multi-units’ configurations. Followed by experimental test cells application for the cooling system and monitoring for testing thermal performance. The simulation results showed significant enhancement in air flow and air speed inside the test room compared to conventional windows, while the test cells monitoring showed an average reduction in indoor temperature and humidity with 2 degrees and 15% respectively. Further monitoring is needed for other alternations of the eco-cooler funnel design for better performance.

KEYWORDS: Passive cooling, clay funnels, CDF, living labs, vernacular thinking

1. Introduction and study background
Millions of low-income populations in hot climates worldwide in poor neighborhoods and informal settlements face serious indoor and outdoor heat stress. Many severe consequences related to mental and physical health occur due to indoor heat stress. This makes it hard or oftentimes impossible for people to study, work to earn a living or even to sleep well. In some extreme cases, night-time temperatures can be up to 8 degrees Celsius higher indoors than outdoors, due to cheap housing building envelopes that accumulate the heat during daytime and release it to the indoor spaces at night-time [1]. Thermal comfort in summertime has been always a main concern in hot climate zones like Egypt. It has been calculated that, in hot climate regions, from 70% to 80% of total energy consumption is used to operate mechanical cooling systems [1]. Retrofitting solutions to enhance indoor climate can be hard to implement or sometimes expensive [2]. Conventional air conditioning systems are too expensive for urban poor residents to buy or to afford paying their electricity bills. Oftentimes, they do not have an electricity supply as they live in off-grid or deprived areas with no infrastructure. Affordable and low-tech passive cooling systems are the most ideal solutions for such clusters of deprived and vulnerable populations. Natural ventilation and passive cooling have traditionally been two important features in Egyptian vernacular architecture to achieve thermal indoor comfort [3]. Passive techniques and low-tech approaches that are rooted in vernacular and traditional architecture can be used such as rooftop and windows shading, perforated facades and walls, natural cross ventilation, evaporative cooling and shading from vegetation [4].
This paper is discussing an experimental pilot project and proof of concept for an eco-friendly and sustainable passive cooling system taking Cairo, Egypt as a place for application. It is a Do It Yourself (DIY) concept that is designed to be implemented using a low-tech construction approach. This passive cooling system aims at reducing cooling loads and enhancing indoor air distribution in residential units in informal areas. The cooling system proposed is a zero cost, zero energy, and zero-carbon one, made from low impact traditional clay materials. The idea started with a thought on how to reduce the suffering of vulnerable populations living in climatically ill-adaptive shelters. The cooling system was developed to achieve a low environmental impact cooling device to be installed instead of mechanical unaffordable and high environmental impact cooling systems. A clay unit element was used in a repetitive parametric manner forming a canvas/screen to improve the indoor temperature and humidity in a passive easy way depending only on natural power from sun and wind. First the design of the cooling unit was made using different configuration and design settings and alignments for a clay element with a funnel shape (called Shisha funnels). Clay funnels were the main unit element aligned in different positions, numbers, angles, size and orientation. Then modelling and simulation were carried out to test the funnel’s efficiency in terms of airflow distribution, followed by urban living lab test cells for monitoring the cooling efficiency of the system. This paper is presenting the results of the first phase explaining the methodology. This idea is different compared to existing research projects of units available in the market. It is an unconventional and innovative way of thinking in how to provide comfort in a cost efficient and DIY environmentally friendly manner. The target is to reach indoor thermal comfort of 26 degrees compared to average of 38 degrees in peak summertime in Cairo.

2. Methodology

2.1. Simulation preparation

We investigated the possible traditional clay funnel forms and found Shisha head to be a suitable form. In addition, it is available in the market at an affordable price (1 EGP= 0.02 Euro). We obtained 11 unburned Shisha row clay units and sliced them vertically in half to be able to scan their cross section and then to draw their exact dimensions for modelling. There are mainly three different forms that come in different sizes as shown in Figure 1. We kept them indoors for drying to avoid cracks. After one day, we cut them vertically by using thread and then we cut out any extra clay with a small knife. After two days we put them outdoors to dry but not under shade to avoid direct sunlight. After more than one week, we scanned all of the units using top view, side view and bottom view as shown in Figure 1.

Figure 1. Collage photos showing the selection process of the shisha funnels and preparation for scanning and measuring their dimensions
2.2. CFD simulation

A computational Fluid Dynamics (CFD) software package (ANSYS FLUENT 2019 R3) was used in this study to simulate the airflow performance for different shisha funnel units. The four stages below were followed to understand the air behavior inside a Shisha funnel.

Stage 1: Basic CFD simulations were performed for a 3D model of the Shisha funnel. The main goal in this stage is to test the procedures for the 3D CFD analysis. However, it was easier to model and test different Shisha funnel configurations as a 2D geometry for simplification. So further stages were mainly simulating 2D.

Stage 2: The procedures for 2D CFD simulations were performed for a single Shisha funnel. 2D geometry was drawn for both solid and fluid domains. The SIMPLE algorithm was applied for the pressure–velocity coupling in the segregated solver. The second order upwind scheme was adopted for the discretization of the governing equations. The standard k-ε turbulence model was applied to model the transport of turbulent kinetic energy, which is one of the most effective methods for natural ventilation simulations [5]. Uniform inlet velocity for the boundary condition was assumed to be 3.37 m/s (the average wind speed in Cairo according to the weather data files.) However, at this stage, some results were identified but the computational domain and the boundary definition needed to be more developed.

Stage 3: From the 7 selected Shisha funnels, we have selected the biggest and the smallest to be simulated. A 3x3 meter shoebox resembling a conventional room size was modelled with a one-meter outlet window. The whole domain had dimensions equal to 100 times the Shisha funnel height. The approximate height of the Shisha funnel is 7cm and the domain dimension is 7x7 m placed just before the air reaches the tested window as shown in Figure 7. Two air flow scenarios were simulated, one when airflow is perpendicular, and one is 45 degrees. Each scenario has three cases. The first simulated case was a fully opened window with 1 meter width as conventional window size. The second and the third case are 1 meter window openings with 7.5 cm and 5 cm height Shisha funnels respectively.

Stage 4: The developed procedures of the CFD analysis were then tested for a smaller shoe box (1x1 m) for both single and cross ventilation techniques as shown in Figure 8. The new domain was developed so the show box room is in the middle for more accurate CFD outcome. The final iteration for the show box was 60x70cm (width x height) with window dimensions of 21.5x30.5cm (width x height) consisting of 4 Shisha funnels. The window size was ⅓ of the facade size resembling the real situation.

2.3 Test cells

After the simulation and deciding on the optimized form of the eco-cooler, the construction of the prototype started. On a roof top of one of the dense residential areas in Cairo three test cells were built. Two different forms of the eco-cooler were installed in two test cells and one was left to represent a base case. The idea of DIY was also tested if it is applicable and feasible. Several trials were made to construct the eco-cooler unit to research an easy and quick way. 60 cm *70 cm test cells are built with typical red brick walls and reinforced concrete roof construction representing conventional buildings in informal areas in Cairo. The three test cells were monitored for three months from August till October 2020. Temperature and humidity were measured using Tinytag data loggers with 5 min time intervals. We could not monitor the outdoor temperature and humidity due to an error in the outdoor loggers. That affected the comparison between indoor performance and outdoor climate. It is considered one of the limitations of the living lab work. A follow up monitoring was carried out from May to June 2021. However, this urban living lab helped in testing the eco-cooler in a real climatic condition better than lab experimentation. The forming process of the eco-cooler is shown in Figure 2 and the two different eco-cooler installations are shown in Figures 3 and 4.
3. Results and discussion
The CFD simulation for the latest 60x70cm shoe box room showed the velocity contours of the vertical plane inside 4 different test cells for cross ventilation, one representing a typical case using a conventional window and the three others using Shisha funnels in different configurations to compare the performance of different Shisha funnel configurations. The results of the simulation showed that using Shisha funnels on both sides of the show box created the most uniform air distribution (see Figure 5 (d)). When Shisha funnels there were 4 shisha units as inlets and one as an outlet, the least air distribution was observed (Figure 5 (b)). When one side was used with 4 Shisha funnels and the other side was left open, it achieved high air velocity and an air distribution is better than in 5 (a) but a lower speed compared to 5 (d) when both sides have 4 shisha funnels. Figure 5 (a) shows the highest air velocity in the center of the room, but a non-uniform air distribution compared to 5 (c) and 5 (d). When one side was used with 4 Shisha funnels as shown in cases 5 (c) and 5 (d), it accelerated the air velocity
in the upper level of the box compared to the fully open window 5 (a). Although Cases 5 (c) and 5 (d) achieved a better air distribution in the whole room, 5 (a) achieved the highest air velocity and distribution in the lower part of the room. However, it seems that Shisha funnels are not increasing the air velocity inside the room compared to the fully open window, but it shows a good potential for utilizing the shape features to redistribute and orient the airflow inside the room. Especially for cases when airflow is not perpendicular to the front side of the room.

![Figure 5. Final simulation outcome](image)

The two eco-cooler test cells monitoring showed a similar performance in temperature and humidity compared to the base case. The average temperature and humidity difference in the two test cells with the eco-cooler is 2 degrees and 15 % humidity reduction compared to the base case. The test cell with 13 funnels showed a slightly better performance in humidity and dew point due to extra openings that allow more air flow. A better performance could be achieved if we used evaporative cooling. At the time this paper is submitted, we are running another monitoring round using water sprinkles on the clay funnels. The clay has a regulating thermal property and with evaporative cooling a drop in temperature is expected. The monitoring results will be presented at another stage. Figure 6 shows a short movie for the construction process of the test cells.

![Figure 6. Short movie documentation for the proof-of-concept construction process.](image)

4. Conclusion
The study showed an experimental trial for using Shisha funnels as passive cooling systems for informal settlements in hot climates. CFD simulation was used to test the performance of the passive cooling unit design in different iterations. The simulation was followed by DIY urban living lab testing and monitoring. The simulation outcome of the study showed that when Shisha funnels were used on two opposite sides of the room wall using cross ventilation strategy, a higher air distribution was achieved.
in the room compared to conventional window openings. The onsite monitoring for the eco-cooler system showed a reduction of 2 degrees in temperature and 15% in humidity compared to the base case. The study concluded that passive cooling using low-tech approaches can be an affordable way to reduce cooling demands in informal areas. In addition, there is a possibility to reduce the reliance on active mechanical cooling systems if the passive cooling efficiency is enhanced to create an average temperature difference of 10°C between outdoors and indoors. Mechanical means depend on electricity generated mainly from fossil fuels in Egypt. Architects should invest time in researching passive strategies to reach the best possible combination of low energy and natural climatic control for their buildings to attain cool indoor environments without using fossil fuels. This presented system needs further testing for different configuration of Shisha funnels as well as for thermal performance for the funnels given the good thermal properties of clay as a material.

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