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Wind Catcher and Trans-evaporative Cooling Residential Integration in Arid Region

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ABSTRACT

The wind catcher potential for providing occupants comfort conditions is been investigated under trans-evaporative cooling for two-level simple dwelling in arid region. The wind catcher runs on the reverse chimney concept in which the upper wind is captured (by means of passive or active louvers) and is impregnated with moisture that consequently reducing its temperature and increasing its density. This results in a cold downdraft stream in the tower which is used to the conditioning of the dwelling space. This work uses a high fidelity computational fluid dynamics (CFD) of multiple species and two-phase flow to examine the performance of the wind catcher subjected to water injection in the form of mist of 10micron droplet size. The air flow is governed by the none-isothermal Navies-stokes equations which are coupled with energy equation in a conjugated heat transfer in accounting to the inner building walls and the convective conditions for the rest of the building. The water droplet is governed by the discrete phase that also in direct coupling with the continuous phase representing the wind. Flow parameters including velocity, temperature, relative humidity and droplets dispersion are evaluated and their distribution is presented. The setup is tested at different regional conditions manifested in the incoming wind speed, present relative humidity level and temperature sensitivity. Results show that in the average UAE summer conditions (42o C and 50% R. humidity) the role of wind catcher in evaporative cooling was deemed unimportant. However under pre-dehumidification near 25% R. humidity a significant temperature drop of 10 o C and reasonable R. humidity of near 60% can be obtained when integrating wind catcher to isolated dwellings.

1. INTRODUCTION

Wind catchers, Badings or Baud-Geer, found in Middle East are historical signature of the importance of cooling for the comfort of human being. In the age of greenhouse gas emission mitigation, fossil fuel energy offsetting, and renewable energy several evaporative cooling solutions are observing innovative renascence. A good review of these structures are given in the work of Roberts [1] covering the simple form that provides sensible heat and natural downdraft to the trans-evaporative form. The new concepts enable better arrangement of the introduced moisture in the form of mist to ease its evaporation and temperature reduction that equivalent to the latent heat of evaporation. Amongst the pioneers who analyzed and design cooling towers is Bahodori [2]. He used aggressive wind values that exaggerate the application in middle-east. Other forerunners who investigate the air flow rate and temperature are Kent and Thompson [3]. They stipulated their design in the arid western US states (Arizona and Nevada) as well as Saudi Arabia. Badran [4] under a strict assumption of the flow have evaluated analytically the role of height that the wind catcher plays for the different regions in Jordan. The previous work however fails to account to the change in density and temperature nor does it provide their distribution. This information is the essential components in assessing the performance of the wind catcher. Ghadiri et al. [5] worked on CFD modelling of a four sided wind catcher. Their work was focused on determining the applicability of CFD in analyzing wind catchers. They studied the model under various turbulence models and varied the angle of the incoming wind. They found that the CFD models gave highly accurate results for perpendicularly entering wind but were not so accurate for wind entering at other angles. Su et al. [6] worked on CFD based flow rate validation of MonodraughtTM wind catcher, which is a commercially available wind catching setup. They did both experimental and CFD modelling for this device and found that CFD analysis was much in agreement with the experimental flow rates recorded. Montazeri et al. [7] worked on a wind tower of a similar design as a MonodraughtTM in Iran. They did experimental testing, analytical modelling and CFD analysis. They found that 20 % higher efficiency could be achieved when the wind catcher inlet is placed at 900 incident angle to the air flow direction. This work is inline of the above sited work but with more focus on simple dwellings and shows the velocity, relative humidity, and temperature distributions under different wind, temperature, and relative humidity inlet conditions to the wind catcher.

2. METHODOLOGY AND PROBLEM SETUP

The two dimensional baseline cutaway of the geometry with dimensions and boundary conditions is depicted in Fig. 1 (similar geometry of Badran's [4]). It sets on 10.95mx11.75m including the cool tower. The two floors are in direct access to the downdraft of the tower through two openings as seen in the Fig. 1. They are all thermally coupled through the flowing fluid and through the conductive structural walls of the tower and ceiling of the 1st floor. The geometry is also subjected to the equivalent walls conductivity and convective surrounding environment. The baseline geometry is subject to incoming wind which is first is captured and directed into the tower through louvers or vanes which tunnel the flow downwards. Following the tower entry and as the flow streamlined downwards, an injection line of water moisture is encountered at top to impregnate the incoming fluid with the stipulated moisture amount. The tower length provide enough residence time for the water droplet to evaporate. The water injector line is directed downwards at low velocity of 10m/s, 10micros droplet size, and a total baseline mass of nearly 0.01kg/s that insures near an acceptable relative humidity level downstream in the conditioned space. The fluid exit from the domain via the two window openings for each conditioned floor. The ground is considered thermally insulated concrete different from the surrounding convective walls, kinetically however is subjected to noslip and no-penetration velocity wall that similar to all the surrounding walls.

2.1. Governing Equations

Two formulations are used to solve the two-phase flow; the Eulerian that governs the continuous gaseous phase and it consists of two species (air and water vapor) and the Lagrangian that track the dispersed or discrete water droplets phase and solve for their trajectories. The flow field is considered as a steady, two dimensional, turbulent and non-isothermal of two species. The conjugate heat transfer model is also seen in some previous works related to evaporation [8].

2.3. Boundary Conditions

As the flow operating velocity and the expected flow field is relatively low (0-10m/s) the flow is considered incompressible. It is driven by the assigned velocity, relative humidity or moisture fraction, and temperature values (Dirichlet) at the very top entry of the wind catcher. The two outlets/windows of the computational domain are specified as outflow at an equal proportion for the flow of 50% to insure proper conditioning and the solution near these windows are not affected by the back/reverse flow conditions. Practically, this can be achieved by means of a simple suction fan. The geometry walls are all subjected to zero velocity and thermally either insulated wall (i.e. ground), or coupled wall (i.e. ceiling), or convective wall (i.e. the surroundings geometry). The mist is introduced via line injections which are defined (injection angle, velocity, mist size) and uniformly distributed at the very top near the entry of the wind catcher (see Fig. 1). Droplet evaporation has been considered with uniform droplet diameter distribution. The droplet diameter is preset at 10 μm with a cone angle of 60°. The water is sprayed at a rate of 0.1 kg/s with a velocity of 2 m/s and temperature 300 K. The water droplets have been assumed to have inelastic collisions with the walls of the wind catcher. Hence, the reflected water droplet will have only tangential component of the momentum.

2.4. Computational Domain and Mesh Sensitivity

The grid consists of a quadrilateral structured surface mesh type. The baseline mesh is shown in Fig. 1 with a total cells of 48,896, 99,012 faces and 50,115 nodes. The maximum and minimum cells areas are 0.0002 m2 and 0.0164 m2 , respectively. The discretization and its clustering in the grid was normally kept to the wall and smoothly extended in the anticipated high gradient velocity and pressures to ensure good accuracy in the results. Furthermore, The baseline grid is modified and three other levels were generated and denoted as Coarse, Coarse-I, and Fine by respectively halving the number of grids in both directions, halving in the axial direction, and doubling in both directions from the baseline mesh clustering/inflation. The solution was carried using the commercial CFD code FLUENT based on finite volume approach. Segregated solver which provides good robustness has been used. Reynold-averaged Navier-stokes (RANS) equations with the constitutive eddy viscosity realizable k-ε turbulence model are solved with Boussinesq hypothesis and discrete phase injections. The semi-implicit method for pressurelinked equations (SIMPLE) algorithm is chosen for pressure-velocity coupling and second order upwind discretization scheme is employed for spatial derivatives properties. The convergence criterion is set at 1x10-5 residual for the continuity, and three momentums and energy scalar equations. Sensitivity analysis is carried out to verify the solution mesh independency using the same boundary conditions. The weighted mass average values at the bottom and top outlets are used to illustrate the discrepancy . As the temperature and relative humidity were more consistent with less than 1% error across all mesh levels, the velocity values were used as the error indicator. As seen in table 1 , the maximum obtained error between the fine and baseline was 2.3% (±0.0544m/s) in the bottom room exit and 4.4% in the top room exit. The error however was more exaggerated for the coarse and half coarse mesh levels reaching as high as 9.8% and 5.7% in the bottom room and 55% and 27.9% in the top room, respectively. Therefore, the baseline mesh can be confidently used to carry further analysis without sizeable influence on the subsequent results.

3. Sensitivity to the inlet velocity

The inlet velocity for the wind tower is geography dependent which makes it uncontrollable unless there is addition of diffuser or nozzle shaped inlets to the wind catcher that promote harnessing more wind. Through these additions the velocity can be modified to suit the needs. Here, in this study we directly model the implications of such additions by varying the inlet velocity of air. This study also corresponds to the unprecedented changes in wind speeds occurring due to weather conditions. Three wind speeds were considered 2, 4 and 6 m/s and these are characteristic to the UAE region. The flow rate if the injectors was fixed at 0.01 Kg/s and the tower height was 12.25 meter. The contours for temperature and relative humidity are shown in Fig. 7 whereas Fig. 8 and 9 show the variation of temperature and relative humidity in different rooms for different cases. As expected, it was observed that with increase in velocity there was an increase in room temperature and a decrease in relative humidity. Similar to the mass flow rate sensitivity study the temperature and relative humidity in both the rooms remained closely identical. The maximum room temperature was 38.65 o C and relative humidity 34.03% (bottom room) for velocity at 6 m/s and the minimum was 31.970 C and relative humidity 58.41% (top room) at velocity of 2 m/s. A higher velocity implies higher influx of water in the form of relative humidity, but at the same time, it also implies higher influx of high temperature air that occupies a larger mass fraction. When the mass flow rate of injected water is constant then higher velocity results in the increase of temperature which exactly what the results are showing. Therefore, lower velocities are better for the effectiveness of the wind catcher or alternatively one needs to adjust/increase the water injection with the increase of incoming velocity to take advantage of higher incoming velocity. Table 2 lists the summary of the temperature and relative humidity for all the considered cases in this work.

4. Conclusion

The potential of wind catcher in providing occupants comfort conditions is been numerically investigated here. A non-isothermal coupled steady Navies-stokes flow of two species used to evaluate the human comfort in a simple two-level dwelling. Using the arid climate conditions of the UAE in particular, the flow parameters including velocity, temperature, relative humidity and droplets dispersion are evaluated and their distribution were presented. Initially at nominal temperature and relative humidity of 42 o C and 50% respectively, the role of wind catcher in evaporative cooling was deemed unimportant. Suggesting a constant temperature pre-dehumidification is necessary and taking advantages of recent developed in hydrophilic materials. As the entering relative humidity level is adjusted/reduced at presumed value near 25%, the potential of evaporative cooling is exasperated. At these conditions (42o C and 25% relative humidity) a significant temperature drop of 10 o C and practical relative humidity of 58% was obtained. The influence of the wind catcher's height in providing sufficient time for mist evaporation and homogenizing the flow as well as the undesirable role of the higher velocity under fixed mist mas flow was highlighted.

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