A PERFORMANCE ANALYSIS OF SOLAR CHIMNEY PASSIVE VENTILATION SYSTEM IN THE UNT ZERO ENERGY LAB

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The purpose of this investigation is to find out suitability of the solar chimney natural ventilation system in a Zero Energy Lab located at the University of North Texas campus, to figure out performance of the solar chimney. Reduction in the heating and ventilation and air conditioning energy consumption of the house has been also analyzed. The parameters which are considered for investigation are volumetric flow rate of outlet of chimney, the absorber wall temperature and glass wall temperatures. ANSYS FLUENT 14.0 has been employed for the 3-D modeling of the solar chimney. The dimensions of the solar chimney are 14’2” X 7’4” X 6’11”. The flow inside solar chimney is found to be laminar and the simulation results show that maximum outlet volumetric flow rate of about 0.12m³/s or 432 cfm is possible from chimney. The experimental velocity of chimney was found to be 0.21 m/s. Density Boussinesq approximation is considered for the modeling. Velocity and temperature sensors have been installed at inlet and outlet of the chimney in order to validate the modeling results. It is found that based on simulated volumetric flow rate that cooling load of 9.29 kwh can be saved and fan power of 7.85 Watts can be saved.
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NOMENCLATURE

$\rho$ – Air Density (Kg/m$^3$)

$\mu$ – Air viscosity (m$^2$/s)

$u, v$ – Air velocity (m/s)

$L$ - Characteristic length (m)

$k$ - Thermal conductivity (w/m$\cdot$k)

$h$ – heat transfer coefficient (W/m$^2$- k)

$\alpha$ – thermal diffusivity (m$^2$/s)

$g$ – acceleration due to gravity (N/m$^2$)

$T$ – Temperature

$\Delta T$ – Difference in temperature

$\beta$ – thermal expansion coefficient (1/T)

$T_s$ – surface temperature

$T_\infty$ - bulk temperature

$P$ – pressure

$\lambda$ – wavelength (m)

$\theta$ – incidence angle

$\varepsilon$ – emissivity

$S$ – source term

$\varepsilon$ – Turbulence dissipation rate (m$^2$/s)

$\eta$ – effectiveness factor

$S_{ij}$ – Mean rate-of-strain tensor (1/s)

$A$ – solar irradiation

$B$ - Atmospheric extinction coefficient

$\beta$ – solar altitude
Edn – direct normal irradiation
Ed- diffuse solar irradiation
Er – ground reflected solar radiation
\( \rho_g \) – ground reflectivity
\( \eta_f \) = Fan total efficiency
\( \Delta P_t \) = Pressure rise in the fan, Pascal
Q = volumetric flow rate, m\(^3\)/s
Wf = Fan power output
\( dt \) = Difference between outside and ambient temperature, °F
\( h_s \) = cooling load, Kwh
CHAPTER 1
INTRODUCTION

“There can be economy only where there is efficiency” is aptly quoted by Mr. Benjamin Disraeli. Today’s world is facing a grim question of energy efficiency. The increasing energy prices and volatile business scenario and fluctuating oil reserves have pushed mankind to think about sustainable energy policies. Building energy consumption, industrial processes and transportation comprise majority of overall energy consumption of whole world, obviously depending on energy consumption pattern of different parts of the world. Among all these factors, the building energy efficiency has attracted a considerable attention of international community and the scientific and corporate community has responded well to this issue. This had led to increase in awareness and use of sustainable building features like solar chimney, wind catchers, Trombe wall, etc. and efficient system like geothermal heat pumps.

The intention of this thesis is to analyze the solar chimney in a Zero Energy Research Laboratory in the university campus. To understand the performance of solar chimney is main point of this thesis. Many of the solar chimney studies done world wide are concentrated on a stand alone basis or study of an experimental apparatus of the solar chimney. There are not many studies which are carried out in a Zero Energy Laboratory. Also, there are not many studies done in a real habitable buildings which includes solar chimney. So, it becomes necessary to study the performance of a solar chimney in a real building. Here at University of North Texas Discovery Park campus, the Zero Energy Research Laboratory is a real building. In this case the study on solar
chimney is carried out with the help of experimentation and validated with the help of simulation.

The experiments are carried on selected days of months of April and May. Each one of four days is called as Case 1, Case 2, Case 3 and Case 4. The HOBO sensors for temperature and air velocity measurement are used. Then Simulation is carried out using ANSYS FLUENT 14.0. The simulation results are validated with the experimental data.

The significance of this study is the use of materials in the construction of this solar chimney. The conventional chimneys are constructed using black colored absorber wall to induce maximum buoyancy force and clear glass glazing to reduce the heat losses from the flow domain. But conversely, here the absorber wall has white paint and the glazing consists of low emission glass. These materials are in consistency with the whole building material. This makes this study significant, as it is intriguing to investigate the ventilation rate produced by such a chimney. And in this way, it is interesting to see if such a chimney can provide sufficient ventilation for a single storey, 2-room building.

1.1 Objective

The Zero energy Research Laboratory is a unique lab in itself, and the building feature which is considered in this study, the solar chimney is also a challenging part to analyze.

- The main objective here is to study the performance of the solar chimney in the Zero energy Lab.
• The main parameters of study will be the temperature of the “Absorber wall”, and the temperature of the glass walls.

• The flow inside the chimney will also be a core part of study, the author wants to investigate the nature of flow and how does the flow takes place actually.

• Volumetric flow rate of the chimney is the main parameter which will demonstrate its ventilation effectives i.e. its ventilation capacity.

• Effect of materials used in the current solar chimney on the performance of solar chimney

1.2 Assumptions

- Steady state flow
- 1-D heat transfer through glass cover and absorber wall
- Laminar air flow
- Constant temperature boundary conditions
- Inlet temperature is equal to ambient temperature
- Pressure different at inlet and outlet
- Outlet pressure equal to static pressure outside
CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

The study of solar chimney has been carried out since last past two decades. Due to tremendous increase in energy consumption, it has became relevant to use natural ventilation as a technique to save building energy consumption. Here, the review is arranged into three parts i.e.: applications, experimental studies and mathematical studies. It is found during the literature review that most of the research is carried out experimentally and it is supported by simulation. For simulation various soft-wares are used which commercially or academically available like FLUENT, MITFLOW, PHOENICS, ACTION, etc. The simulation is proved to be dependable technique of understanding and predicting the behavior of solar chimneys. Also many authors have designed the physical model which is a mathematical model. These models are solved using the conventional heat balance equations and also by solving the thermal network. The mathematical studies are also supported by simulation. It is shown in literature that the simulation results are in agreement with the experimental and mathematical model. This easily makes the simulation as most reliable prediction tool for the complex behavior of solar chimney. Computational fluid dynamics is the main tool for the prediction of analysis of chimney and mostly FLUENT. The studies are done all over the world like UAE [1], Lisbon [2], Japan [3], India [4,5], China [6]. The main parameters which influence air flow rate, absorber wall temperature, inlet area, outlet area, height of chimney and absorber wall material.
2.2 Experimental Studies

Experimental studies are the basis of many research papers trying to investigate the solar Chimney. [1] study the combine wall-roof solar chimney in a two storey building in UAE. Here, they have used ACTION psychrometric software to predict the cooling load. The roof solar chimney is an inclined chimney at an angle of 25° and the absorber wall is painted black. The hot weather of Al-Ain city in UAE is capable of inducing high temperature difference in the flow domain causing air changes per hour (ACH) of up to 26. As the authors say, this ACH should perfect in high rise buildings to induce natural ventilation. The optimum height of 3.60 m is found suitable to produce maximum air flow rate of 2.3 m³/s. The air flow rate varies from 0.8 m³/s to 2.3 m³/s. The authors conclude that the cooling load based on ACH of 25.8 and 24.6 was calculated to be 17.5 KW and 13.5 KW. [2] studied the performance of two chimneys. One conventional and other solar chimney. The dimensions were 0.2m x 1m and height of 2m. Tracer gas technique was used to measure air flow rate. Constant emission method in Tracer gas technique was used for this purpose. The chimneys were equipped with anemometers, thermocouples and radiation sensors to measure velocity, temperature and solar radiations. As found by the authors, the total ACH of 29.1 was found in solar chimney on 29/30 Jan and 28.1 in conventional chimney. The authors conclude that this is due low insolation. A Ach of 29.3 in solar chimney and 27.3 in conventional chimney was measured in diurnal period and the air changes in both chimneys equalize during night time due to low solar radiation and lack of heat storage. The authors also conclude that for night operation of chimney the thickness of absorber wall should be high, to account for the thermal storage in absorber wall. For diurnal operation, less thickness
should be considered. They also suggest using insulation for outside brick at south wall to prevent solar gains from leaving the domain. Loss of 60% of solar assistance efficiencies is evident when the insulation is not used. Authors also conclude that during calculations or simulations, wind effects can be ignored as they are very fluctuating in nature. The neglecting of pressure coefficients can results in under prediction of air flow rates. Wenting et al. investigate a multi storey building with atrium. This building has to be designed for fire smoke control. The top atrium part of the building is considered as solar chimney. Constant temperature boundary conditions are used for simulation and surface to surface (S2S) radiation model is ignored in the simulation. Turbulence model is included in the simulation. For the simulation 1/25 th scale model is used. The authors conclude that simulation results are in good agreement with experimental observations and that natural ventilation is possible for this type of multi storey building. Controlling the position of neutral plane is very important in such a building according to the authors [3]. When the area of inlet of the building increases, the difference in pressure decreases and the top of solar chimney witnesses greater pressure difference. There is a possibility of increase in pollution if the outlet area is half that of inlet area of the building [3]. Ziskind et al. study the possibility of passive ventilation in a single storey building. They also intend to study the indoor air quality improvement with solar chimney installed in such a building. Both transient and steady state simulations were performed using FLUENT 4.5, the study is done in Israel. Real size buildings and laboratory scale models both are considered for study. For real size buildings turbulent flow is considered for simulations and incompressible gas law is used. Constant boundary conditions for absorber wall and heat transfer coefficient with surrounding temperature
for all other surfaces are employed. The authors conclude that effective natural ventilation with such a solar chimney is possible in real size buildings and also in laboratory scale buildings. They also conclude that solar chimney could be an effective feature for maintaining indoor air quality and removing harmful gases like Radon from underground of buildings [7]. Chen et al. study a solar chimney with effect of constant heat flux. To simulate this effect, a constant low voltage supply is provided one surface of solar chimney with Hewlett Packard 6671A system DC power supplier. The authors conclude that 45° inclination provides maximum air flow at chimney exit, this air flow is 45 % higher than the vertical chimney as claimed by the authors. They also comment that above 400 mm air gap reverse flow is visible. Dimensions of chimney considered are 1.5m X 0.62 m width and variable air gap from 100-600mm. Smoke visualization techniques is used for detecting the air movement, for this purpose Drager tube is used. It has 15 % uncertainty for 400 mm air gap and 20% for air gap above 400mm. 13 thermocouples used for temperature measurement. TSI8455 air velocity-meter is used for measurement of air velocity. Air flow rate of 0.02-0.05 m³/s was observed at exit and temperature difference between absorber wall and ambient air was in the range of 55-75° C for 200-600 W/m². The maximum air flow was found at 45° and 200mm air gap and height 1.5 m. the authors conclude that prediction soft-wares over-predict the velocities at chimney outlet. But, they say that this should be attributed to the pressure loss coefficient s which are ignored in the simulation [8]. Li et al. study a solar chimney attached to side wall of a building using MITFLOW CFD program developed at MIT. The authors conclude that simulation results are in good agreement with the experimental results in literature. Air gap, width, outlet to inlet area ratio and location of outlet and
inlet investigated here. The dimensions of solar chimney are L-0.5-5.0m, B- 0.1-0.5m, H-2-5m, B/H-0.05-0.25. Turbulent flow is considered here for simulation and it is claimed by authors that maximum air flow occurs when B/H ratio is 1/10. Authors also comment that the height of chimney should be increased to the height at which the cross section area is not more than critical area for this solar chimney. The authors suggest that cross sectional area has significant effect on the transitional /turbulent heat transfer inside chimney flow domain [6]. Wang et al. study the solar chimney with one-sided heating. Steady state study is undertaken with turbulent k-epsilon energy equations. For the study the dimensions considered were H-1.5m, L-0.62., air gap-0.1-0.6m. The solar radiations from 200-600 W/m2 were considered in simulation. Absorber wall was made of stainless steel and 0.12mm thickness and glazing consisted 3mm thick plexi-glass. The domain was insulated with 100mm fibre glass to reduce heat loss from chimney. Maximum relative error between simulation and experimental results was observed to be 18.5% and average error was 9.5%. Effect of radiation was ignored in the simulation. Highest velocity was found near the heated wall and also highest temperature was found to be at absorber wall. The ratio of breadth to height of 0.5 was found to induce highest air velocity onside the solar chimney. Air gap of big dimensions caused back flow. Mass flow rate increases with solar radiation and height of solar chimney. Increase in stack effect and decrease in pressure losses are most important parameters for increasing the mass flow through chimney outlet [9]. Ding et al. propose a prototype building to study the possibility of using solar chimney for natural ventilation and smoke control in event of fire incident at the same time. Here, the considered prototype building is a eight storey building with atrium at the top, this top atrium is
studied as solar chimney which is three storey high in height. For the solar chimney, south surface and roof are made of glass. The Froude number is considered for smoke movement behavior. Grashoff number is also considered for natural convection. Standard turbulent K-epsilon energy equations are used for CFD simulations. For temperature measurement k-type thermocouples are used and for velocity measurement anemometer is used. Inlet temperature for solar chimney is 27°C and inlet area is 1/45 th of the total floor area. Smoke control experiments are performed by using Ethanol and the time averaged heat release rate is used as intensity of heat source in simulations. Boussinesq approximation is used for simulating buoyancy driven flow. For natural convection, all wall surfaces at constant boundary condition and all other surfaces adiabatic and for smoke control simulation all surfaces are considered adiabatic and pressure is ambient. The heat release rate for full scale model is 2187.5 kW and for laboratory scale model it is 700 W. good agreement is observed between simulation and experimental results. When the ratio of outlet to inlet area reaches 2, the neutral plane remains in building and this prevents the smoke to pollute other internal areas in building. Also, as long as the atrium pressure remains negative compared to the outside pressure, this system will work according to the authors [10]. Ahmad et al. study circular PVC pipe solar chimney in the tropical climate of Malaysia. Here, the authors have constructed two solar chimney models with different color codes, one with black color and other with white color. The experimental data is recorded from 10:00 am to 8:00 PM using Dickson temperature and humidity data logger. The authors observe maximum temperature occurring at 1:00 PM in afternoon and black color induces maximum temperatures inside chimney domain. Black color is a very good
absorptant and is found effective for solar chimney operation while white color is good reflectant and induces relatively less temperature gradient inside chimney. The authors observe that temperature difference between black colored and white colored solar chimney is about 5-10°C. They conclude that increase in black colored solar chimney's surface area would further enhance its ventilation capability and thus, natural ventilation with solar chimney is a feasible option [11]. Nigroho et al. investigate the natural ventilation technologies in tropical climate of Malaysia. Solar chimney, solar roof and trombe wall (solar wall) are considered here for study. The authors conclude that the solar chimney increases both air flow and also heat gain inside the room while solar roof reduces heat gain along with air flow. The solar wall increases the air flow but this depends on its position with respect to solar radiation. The authors conclude of using combined strategy of using solar chimney with solar roof for further study [12]. Chunglloo et al. study a single storey detached university laboratory building with solar chimney and cool ceiling technology with water spraying. The solar chimney is at south roof and water spraying at north wall. The solar chimney inclination is at 45°. The difference between experimental and simulation results is found to be 13-18%. The decrease in temperature is found to be about 2-4°C due to water spraying while the increase in air flow was found to be 6-17%. K-type thermocouples are used for temperature measurement and the test was carried out in May-June 2006. Yokohoma – DR 130 data logger is used for data recording and FLUENT 10 for simulation. RNG K-epsilon turbulence model is used for simulation the system. The authors conclude that this is an effective system and can be used to induce buoyancy driven flow [13,14]. Khanal et al. present a very detailed review of solar chimney study in past two decades. The authors
comment that cooling energy of 10% and fan power of 15% will be saved by use of natural ventilation. Thermal buoyancy or wind affect the natural ventilation flow. The authors also comment that solar chimney performance depends on various parameters such as orientation, materials, climate, location, size of space to be ventilated and internal heat gains, etc. the authors claim state that analysis of solar chimney is based on experiments, analytical study and simulation. There are two basic areas of study when solar chimney is considered, explain the authors and these areas are geometry and angle of tilt. Khanal et al. explain further that absorptivity of the surface has greater effect on chimney performance. Linear relationship exists between solar efficiency and absorptance when the absorptivity value is greater than or equal to 0.8. Air flow rate has improvement of about 57% by increasing the absorptivity of absorber wall. Positive effect on solar chimney is observed when the ratio of absorptance to emittance has highest possible value. The authors mention that there is not much research done on effect of absorptivity of glazing on ventilation rate, but they state that the absorptivity of glazing has negligible effect on ventilation rate. They also mention that wall thickness is less influential parameter on ventilation performance than other parameters. Khanal et al. also state that experimental studies are the most preferred studies for solar chimney. Large scale models generate quality data and small scale models are usually supported by mathematical analysis and computer simulations. Reverse flow is observed in wider chimneys at outlet is not explained in earlier studies. The requirements for ventilation and guidelines and design parameters to achieve them are not explained in a clear way, as is stated by Khanal et al. The Air changes per hour (ACH) of about 3-60 are achievable from the studies according to authors [15]. Saifi et al. study inclined solar
chimney in Algeria. Here, 2 X 1m case is exposed to sun, the absorber wall is made of galvanized steel and painted black and glazing is provided by Clear glass. The chimney is insulated by 40 mm polystyrene sheet. Air gap of chimney is varied by 10mm, 20mm and 30 mm. For CFD simulation FLUENT 6.3.26 code was used. Turbulence energy equations are considered and Boussinesq approximation is employed for simulation. The authors conclude that air flow of the chimney increases with the increase in the air gap between the absorber wall and glazing. 45° is optimal tilt found which induces maximum air flow. The authors also observe maximum air flow near the absorber wall [16].

2.3 Mathematical Studies

Bernandes et al. developed and analytical and numerical method to study the solar chimneys. They develop a thermal network to solve heat balance equations for different nodes in the geometry considered. Then these equations are solve during matrix inversion method. The intension of authors here is to compare the mathematical values with experimental data from Manzanares, Spain and validate the model and prove this for large scale commercial solar chimneys also. The authors consider two types of collectors : a) single channel- here air flows through top glass and bottom absorber and b) double channel- here air flows between absorber and bottom cover. Heat balance equations were written for type (b). Different parameters like height of chimney, distance between absorber and ground, optical properties of turbine and factor of pressure drop at turbine were investigated. On selected days the energy generated was calculated and the divergence of -1.6- 1.9 % was observed when compared to
experimental results of Manzanares. The authors conclude that maximum power can be produced when the factor of pressure drop at turbine reaches 0.9 and other parameters like, distance between absorber and ground, water storage system and double cover area are ineffective on chimney performance [17]. Ong et al. study the solar chimney mathematically and validate experimentally. Here, a simple physical model for solar chimney is created. It is similar to the Trombe wall. Steady state heat transfer equations are solved. Thermal network is designed and performance based on air temperature, wall temperatures and glass temperatures and heat collection efficiency of solar chimney has been studied. Solar radiation of 400 W/m² are considered in analysis. The dimensions for solar chimney are length of wall 4 m and openings at bottom and top are equal to 0.025 m². The results of mathematical model and experimental results show that mass flow rate of 0.014 kg/s can be achieved. The authors conclude that temperature distribution at chimney surface depend on solar radiations and absorber wall temperature is higher than the glass temperature. The efficiency of chimney decreases with increase in temperature. The flow of air in the air gap is influenced by wall temperature only when the gap is small, the influence of wall thickness reduces as the air gap increases [18,19]. Bansal et al. propose a mathematical analysis for an unique system created by combining solar chimney with wind tower for natural ventilation. The authors proposed a mathematical procedure to estimate the pressure difference and calculate the mass flow rates, temperatures and velocities. Heat balance equations were solved for the model selected. Effect of wind was considered in the investigation. The solar chimney is found to be more effective at low air velocities and air changes of upto 35-73 can be achieved in present study as reported by Bansal et al.
At solar radiations of 700 W/m², the solar chimney achieves 0.75 kg/s air mass flow rate according to authors and the wind tower achieves 0.75 kg/s at wind speed of 1 m/s. The authors conclude that such a system is possible and interesting for integration in a real size building [20]. Bansal et al. propose mathematical analysis for a solar chimney. Here, the authors investigated solar chimney with variable chimney openings. Variable values of discharge coefficients are considered to evaluate chimney performance. The authors conclude that 140-300 m³/hr of air flow rate can be induced by chimney with 2.25 m² solar collector and solar radiation of 200-1000 W.m². The authors write mathematical equation for volume flow rate with the help of Bernoulli’s equation and Continuity equation using Principal of conservation of mass. For surface temperatures of absorber wall and fluid flow energy balance equations are solved [21]. Mathur et al. perform a mathematical study on a solar chimney and validate with experiments. Nine combinations of height and air gap were tried any authors and maximum output was found at ratio of 2.83. for 700 W/m² solar radiation 5.6 ACH was investigated by authors. The study takes place in tropical climate of India. K-type thermocouples are used for temperature measurements and hot air anemometer for velocity measurement. Dimension of solar chimney considered are 1m X 1m X 1m. for mathematical model, the mathematical equations were written to calculate mass flow rate and surface temperatures. Energy balance equations were written for absorber, glass and air flowing through chimney. Re arranging these equations and solving them by matrix inversion resulted in mass flow rate equation and then this was validated by experimental results. Laminar flow is considered and 1-D heat transfer equations is assumed. Constant boundary condition is used and the inlet temperature for chimney is ambient
temperature. The authors conclude that air flow increases with the increase in height of chimney and increase in air gap of chimney. 45° inclination gives most favorable results more than 30° and 60°. The authors state that 55-150m³/hr air flow rate can be achieved at 300-700 W/m² [4,5]. Arce et al. investigate a big solar chimney which is representative of 10 small solar chimneys. Here, the chimney is divided into 16 control volumes and then using theory of thermal resistance a thermal network for solar chimney was developed. Energy balance equations at each node were solve to fing glass temperature, fluid temperature inside chimney, absorber wall temperature, etc. The constant necessary for solving these equations were assumed from the values found in literature. The authors verified results from solving these equations with experimental results of Ong et al., Hirunlabh et al., etc. 27th June was considered for investigation. The volumetric flow rate increases from 61 to 147 m³/hr for 700 W/m² [22].

2.4 Applications

Solar chimneys have attracted attention of whole world in last two decades. The primary intention of such a technology is to induce buoyancy driven flow and by that means provide thermal comfort in the building indoors. Most of the studies like found in [2][23][27], etc are concentrated on natural ventilation. The solar chimney is found to be very effective feature in this regard but, there are very exciting research being done considering the possibility of using solar chimney for smoke control in an event of fire incident as done here [3][10].
Bansal et al. design a novel system which integrates solar chimney with wind tower system to induce natural ventilation [20]. A comprehensive review of solar chimney power plant technology by Zhou et al. in [24] shows that solar chimney power plant technology is commercially viable. Though the life cycle cost of solar chimney power plant is high, it can be compensated with no greenhouse gas emissions and further income from generation capacity. Thermal storage techniques like solar ponds and water filled thermal storage can further prove beneficial for solar power plants to be operational.

Zhai et al. report a very good study of applications of solar chimneys in buildings in [25]. They report that solar chimney applications can be classified as roof based, wall based and integrated solar chimney systems. Solar roof collectors prove to be beneficial in trapping the solar insolation incident on roof and thus provide thermal comfort and by doing this they also indirectly reduce cooling costs [25]. The optimum dimensions reported by Zhai et al. in this study are $L = 100\text{cm}$, tilt angle $30^\circ$ and air gap not more than $14 \text{ cm}$. They also state that $0.08-0.11 \text{ m}^3/\text{sm}^2$ air flow rate can be achieved. Highest air flow can be achieved by large air gap and equal openings [25]. As the length of collector increases air flow rate decreases, report Zhai et al. The authors also report that solar roof collectors can be used for heating in winter and cooling in summer.

Zhai et al. also mention the use of wall chimneys in buildings. Theses chimneys are installed at south facing walls mostly. They report that installation in North- eastern Himalaya region resulted in $32.5\%$ overall efficiency and $2.3 \text{ kWh/m2}$ energy collection. The authors stat that porous materials can improve performance of solar chimneys and multi-storey solar chimneys and chimneys for multi storey buildings are found to be
feasible options as reported by Zhai et al. Night cooling is also an important operational requirement of solar chimneys [25].

Zhai et al. also report use of integrated solar chimneys. The use of solar vertical chimneys with solar roof collectors was reported by authors to be possible and effective. Use of solar chimney with earth to air heat exchanger, evaporative cooling, adsorption cooling, cool ceiling technique, etc. was also reported by authors [25].
CHAPTER 3
SOLAR CHIMNEY AT ZOE LAB

3.1 (ZOE) Lab Description and Features:

The Zero Energy Research Lab (ZOE) at the Discovery Park campus of University of North Texas is a unique lab in itself. It is only lab built of it’s kind in the state of Texas. It provides student with vast opportunities of research and get hands-on experience to study and analyze many renewable energy technologies and state-of-the-art equipment, all at the same place. This building is a South facing, single storey building. It has floor area of 1200 square foot. The building is equipped with different renewable energy technologies and the building energy monitoring and control system. The main systems include a Geothermal Heat Pump system. For this system, six geothermal wells each 225 feet deep have been created. All these wells are connected to the main building with the help of thermocouples, so that underground temperatures can be monitored 24 hours and various depths. There are two heat pumps in the building viz.: the water-to water heat pump and water-to air heat pump. Both of these heat pumps are connected to the geothermal wells. These heat pumps are utilized to provide the heating, ventilation and air conditioning needed for the building. The next important and unique feature of the building is the radiant floor system. This radiant floor system consist of six zones under whole floor of the building and the length of the pipe for this system is 500 meters. This system is also directly connected to the geothermal wells, the water is supplied to this system through the water-to water heat pump. On the roof of the building, photovoltaic (PV) panels are provided, which are 24 pieces in total and have capacity of 5.6 kWh. The PV panels form basis of the electricity generating
capacity of the Zero energy Research Laboratory. This system is complementing with the residential wind turbine installed at the building campus. This wind turbine is a five blade and horizontal axis system with generating capacity of 3.5 kWh. All of these electric power generating systems are also connected to the district electricity grid. The concept behind this is that, when electric power is generated more on building campus it would be supplied to the domestic grid. In a scenario where local power generation is insufficient to meet building electricity demand, then domestic grid can supply electricity to building. This type of operation makes this research laboratory, a Net Zero Energy Lab. Each system has been provided with separate electric meter, so that accurate electric generation can be calculated. There are various energy efficient materials used for the construction of this building. Here, most evident material, is the Low Emission (LOW –E) windows. These argon based Low Emission windows, which block the long-wave solar radiation entering the indoor space of building. This prevents heat gain inside the building, but these windows allow light to pass through them. So, natural light is available in building but heat gain is reduced. All the indoor and outdoor walls are painted white, so that maximum solar radiation are reflected. By virtue The walls of this, the heating, ventilation and air conditioning energy can be saved. The walls and roof of this building is constructed with steel faced Structural Insulated Panel (SIP). [8] The Steel faced SIP panels are the most cost effective energy efficient and environmentally responsible building systems available. They can save upto 66% of HVAC energy consumption. The building is divided into living area and working area. Working area is larger compared to Living area. The Living area is equipped with all amenities needed for residential purpose like foldable bed, refrigerator, oven, etc. the floor of Living area is
a Bamboo floor. The Bamboo is attractive, strong, renewable source and cost effective. So they have been incorporated. The most energy consumption in building is due to lighting and equipment. Considering this issue, all the lightings are Light Emitting Diode (LED) lights, which are less energy consuming. For further reduction in HVAC energy consumption, Energy Recovery Ventilator (ERV) is provided. The ERV pre-heats the supply air in cold climate and pre-cools the supply air in Hot climate, this also contributes in reduction of energy consumption. To monitor all the systems, a Building energy monitoring system is installed. There are around 180 sensors in the building to measure different parameters like indoor temperature, out-door temperature, solar radiation, etc. Occupancy sensors are also installed, to prevent unnecessary usage of energy.

Figure 3.1: South facing view of Zero Energy Research Laboratory (ZOE)
A solar thermal evacuated tube plant is also installed on the roof of zero energy lab as seen in Fig. 3.2. The solar thermal plant uses evacuated tubes to heat the domestic water supply with the help of solar energy. This plant is also useful for heat support, pool heating, industrial applications and thermal refrigeration [26].

3.2 Solar Chimney

Solar chimney as it is known at the Zero Energy Research Laboratory is not a different system but a feature of the building. This feature can also be used for the natural ventilation in the building.
The solar chimney has height of 14.2 feet X 6 feet 11 inches X 7 feet 4 inches. The inlet of chimney is 3 feet and outlet is 1 feet. The chimney has distinct features than conventional solar chimney. The south facing wall of chimney consists of 6 feet of Low emission glass from top. Also, the inside of the walls of solar chimney are painted white. The roof of the solar chimney is made of steel faced SIP panel. There is one supply pipe for the heating, ventilation and air conditioning which passes through the flow domain of chimney. The other 8’2” of the south facing wall of the solar chimney is a brick wall. The inside walls are made with Gypsum Board.
3.3 Low –Emission Windows

Recently, the low emission glasses have found tremendous applications. The increasing electricity bills and urgent need to reduce costs have culminated in development of Low emission glass. Basically, in such type of glass there are two glass panes and either an inert gas or air is sandwiched between these two panes. Reflective coatings are applied on either the third or second surface based on application. There are two main procedures to manufacture Low emission glasses viz. Pyrolytic Chemical Vapor Deposition (CVD) and Magnetron Sputtering Vapor Deposition (MSVD). The low
—e coatings act as absorbers or reflectors of infra red solar radiations which are responsible for heat generation. The energy costs can be reduced tremendously, depending on where the low coating has been applied. In warm weather, when #2 surface has low-e coating then it act as reflecting agent for IR rays which come from outside. This reduces the solar gain. And while in cold climate, we need to save internal heat energy, this can be achieved by applying reflective coatings on surface #3 which reflects heat energy from inside. This reduces the heat loss from indoor to outdoor [27].

Here, at Zero Energy Research Laboratory the low emission glasses are supplied by Viracon Industries. The glasses contain two ¼” glass panes and the airspace is filled by Argon gas.

3.3.1 Terms Related to Low Emission Glass [27]

- NFRC U-value: It is a measure of heat gain or heat loss through glass due to differences between indoor and outdoor temperatures. These are center pane values based on NFRC standard winter nighttime and summer daytime conditions.
- R-Value: It is the thermal resistance offered by object. It is measured in ft²*hr°F/BTU.
- Shading coefficient: Shading coefficient is defined as the ratio of solar heat gain through a specific type glass that is relative to the solar heat gain through a (1/8”) 3mm ply of clear glass.
- Relative heat gain: (RHG): It is total amount of heat gained through glass taking into consideration U-value and shading coefficient. RHG= Summer U-value X 14°F + shading coefficient X 630.
- Solar heat gain coefficient (SHGC): The portion of solar energy directly transmitted or absorbed that enters into building's interior. These parameters affect the performance of low emission glasses. Higher R-value leads to less heat transmission. At the same time heat gain increases with the increase in solar heat gain coefficient (SHGC). Heat gain reduced with the decrease in shading coefficient.
CHAPTER 4
METHODOLOGY

4.1 Theory

The free/natural convection flow motion can be well described by Navier-Stokes equations in Cartesian form as below:

- Equation for Continuity:
  \[ \frac{\partial}{\partial x_i} (\rho u_i) = 0 \]  
  \text{Equation 1}

- Equation of Momentum:
  \[ \frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = \frac{\partial}{\partial x_j} \left( \frac{\partial u_i}{\partial x_j} \right) + \rho g_i \]  
  \text{Equation 2}

- Equation of energy:
  \[ \frac{\partial}{\partial t} (\rho h) + \frac{\partial}{\partial x_i} (\rho u_i h) = \frac{\partial}{\partial x_i} \left( k \frac{\partial T}{\partial x_i} \right) \]  
  \text{Equation 3}

4.1.1 Dimensionless Numbers

The natural convection flow can be defined by different dimensionless numbers which characterize onset of Natural convection flow and predict the nature of the flow. These can be explained as below.

- Rayleigh Number (Ra):
  \[ Ra = \frac{\Delta \rho g L^3}{D \mu}. \]  
  \text{Equation 4}

Here, the pressure difference can be substituted by product of reference density, thermal expansion coefficient and the difference in temperature in the domain.

Therefore,
\[ \Delta \rho = \rho_0 \beta \Delta T \]  
\text{Equation 5}
General diffusivity can be substituted with thermal diffusivity

Therefore, \( D = \alpha \)

Hence, the final equation comes out to be,

\[
Ra = \frac{\rho_0 g \beta \Delta T L^3}{\alpha \mu}
\]

Equation 6

When the flow is completely laminar and the flow is parallel to the vertical wall,

The mean Nusselt Number can be given as:

- Nusselt Number (\( Nu \)):

\[
Nu_m = \frac{h_m L}{k}
\]

Equation 7

Also,

\[
Nu_m = 0.478 (Gr^{0.25})
\]

Equation 8

- Grashoff Number (\( Gr \)):

\[
Gr = \frac{gL^3(t_s - t_\infty)}{v^2 T}
\]

Equation 9

- Bernoulli Equation:

The Bernoulli equation essentially based on Bernoulli’s principle is basically a statement of conservation of energy principle. According to this principle, the pressure should decrease with increase in velocity. But, this phenomena is an ideal condition. During a flow, there are viscous forces, pressure losses due to contraction, expansion, valves, etc. and then there are assumptions made to consider the flow follows theoretical laminar flow path. This may not be the case in real situation, so the behavior of flow with respect to pressure can be different. The Bernoulli equation is stated as below [36]:
\[ P_1 + \frac{1}{2} \rho v_1^2 + \rho gh_1 = P_2 + \frac{1}{2} \rho v_2^2 + \rho gh_2 \]  

**Equation 10**

4.1.2 Development of CFD Model

Computational fluid dynamics (CFD) is a very powerful software. Here, ANSYS FLUENT 14.0 has been considered to model the solar chimney. First, the model of solar chimney was modeled using Design Modeler and the meshing was adapted using ANSYS Meshing. Boundaries were created and given specific names. Then the model was set up in FLUENT. Here, laminar energy equations were used and the surface to surface (s2s) radiation model was to model external and internal radiations. Second order discretization schemes were used.

Model accuracy is a component of many factors like mesh size, cell orientation, models used, discretization schemes used, transient or steady state simulation, materials, etc. To study the effect of solar radiation on the chimney behavior, solar load model was is a unique feature of ANSYS, was implemented.

First the flow is considered laminar based on the calculations of Rayleigh number, Grashoff number, etc. Then the simulation is run. To check accuracy with the experimental results and laminar flow simulation results, the model is run with realizable K-epsilon model.

Turbulence is an unsteady flow. Most of the engineering flows can be considered as turbulent in nature, this type of flow takes place at high Reynolds number. It is not possible to solve all the equations in varied scales of time and space. This can be very computationally expensive, to resolve this Reynolds Averaged Navier-Stokes (RANS) equations are considered. They are less computationally expensive and precisely
accurate. Here, Realizable $k$-$\varepsilon$ Turbulence model is adapted. This is a two equation model, it is known as “realizable” because it satisfies certain constraints on Reynolds stresses.

The transport equations for this model are [28]:

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho k u_j) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \tag{Equation 11}$$

And,

$$\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_j} (\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_1 S \varepsilon - \rho C_2 \frac{\varepsilon^2}{k+\sqrt{\varepsilon}} + C_1 \frac{\varepsilon}{k} C_3 G_b + S \varepsilon \tag{Equation 12}$$

Here,

$$C_1 = \max[0.43, \frac{\eta}{\eta + 5}], \eta = S \frac{k}{\varepsilon}, S = \sqrt{2S_i S_{ij}}$$

4.1.3 Solar Load Model

Solar load model in the FLUENT is a very efficient tool to compute effect of Sun’s rays on the domain. This model uses solar ray tracing. The ray tracing algorithm predicts direct illumination energy and diffuse illumination energy and applies the same as source term in the energy equation. The source term are added to adjacent cell of each face and then they are added to following cells consequently. The solar position vectors are used, were we can enter the real longitudes and latitudes of the position we need. By virtue of this, the ray tracing algorithm will include effects of direct and diffuse solar illumination. For direct illumination, it uses 2 band spectral model and for diffuse solar radiation the solar load model uses single band spectral model. We can define the wall boundary conditions as opaque or semi-transparent. When wall is opaque no sun rays pass through it. When the wall is semi-transparent, the model allows some amount
of solar rays to pass through it. For Semi-transparent walls it is required to enter direct
diffuse hemispherical transmissivity and absorptivity. This values are required to be
supplied from manufacturers as they may have different set of labels for these
properties [28].

The equations for transmissivity and reflectivity used here are:

$$T(\theta, \lambda) = T(0, \lambda)T_{ref}(\theta)$$  
Equation 13

Where,

$$T_{ref}(\theta) = a0 + a1 \cos(\theta) + a2 \cos(\theta^2) + a3 \cos(\theta^3) + a4 \cos(\theta^4)$$

Reflectivity :

$$R(\theta, \lambda) = R(0, \lambda)[1 - R_{ref}(\theta)] + R_{ref}(\theta)$$  
Equation 14

Where,

$$R_{ref}(\theta) = b0 + b1 \cos(\theta) + b2 \cos(\theta^2) + b3 \cos(\theta^3) + b4 \cos(\theta^4) - T_{ref}(\theta)$$

Equations for calculation of direct normal solar radiation and diffuse solar
radiation are a below:

For Fair weather conditions, the calculation of normal direct irradiation is done
by:

$$E_{dn} = \frac{A}{B \sin(\beta)}$$  
Equation 15

Diffuse solar radiation on vertical surface is given by:

$$Ed = CY_{Edn}$$  
Equation 16

Equation for diffuse solar radiation for all other surfaces than the vertical surface:

$$Ed = CE_{dn} \frac{(1 + \cos \epsilon)}{2}$$  
Equation 17

Ground reflected solar irradiation on a surface is given by:

$$Er = E_{dn} (C + \sin \beta) \rho_g \frac{(1 - \cos \epsilon)}{2}$$  
Equation 18
4.1.4 Surface to Surface Radiation Model (S2S)

The surface to surface radiation model in FLUENT can be used to compute radiation exchange between gray-diffuse surfaces. Here, emission, absorption and scattering of radiation is ignored, so in this way only surface to surface radiation interaction between surfaces is considered. The radiation exchange depends on orientation of geometry, separation distance between two surfaces and the size [28].

The energy leaving surface “k” can be expressed as:

\[ q_{out,k} = \varepsilon_k \sigma T_k^4 + \rho_k q_{in,k} \]  \hspace{1cm} \text{Equation 19}

- Boussinesq Approximation:

Boussinesq approximation is found to be most suitable for buoyancy driven flow or natural convection. Here, the assumption is made that density is constant in all equations except for the buoyancy term in the equation of momentum. The Approximation in the Boussinesq equation suggests that the inertia difference can be neglected but the effect of gravity significantly changes the specific weight between the two fluids in contact [29].

The equation of Boussinesq approximation is:

\[ (\rho - \rho_0)g \approx -\rho_0 \beta (T - T_0)g \]  \hspace{1cm} \text{Equation 20}

\[ \rho = \rho_0 (1 - \beta \Delta T) \]  \hspace{1cm} \text{Equation 21}

Equation 20 can be obtained by using 21 to eliminate density from buoyancy term.

The Boussinesq approximation holds true for the flow only when

\[ \beta (T - T_0) \ll 1 \]  \hspace{1cm} \text{Equation 22}

Equation 22 is true [28].
4.2 Materials

The materials used here in the solar chimney are in accordance to the materials used for the construction of whole building. The materials are different from the materials used in conventional solar chimneys found in the literature survey. The Zero Energy Research Laboratory is a green building, all the materials used in the construction are from the point of view of making the buildings energy efficient.

In case of solar chimney, the absorber wall is painted white in color. All other interior walls in the building are painted white, to reflect most energy incident on surface and that way reduce energy consumption. The material for the absorber wall is Gypsum board. All the material properties’ information was obtained from manufacturer. The main feature in the solar chimney is the low emission windows used for glazing. These are used to let the light enter the building and block heat energy. All the optical properties required for the simulation were requested from the manufacturer. For the roof of solar chimney, Structural Insulated Panel (SIP) with steel face are used. This are found to be very efficient then the wooden counterparts and have proven to be useful in reducing energy consumption. The properties for this material were calculated based on information provided by manufacturer.

In the simulation air properties are considered at 20°C, and Boussinesq approximation is considered. The properties of materials are tabulated as given below:

<table>
<thead>
<tr>
<th>Properties</th>
<th>Air</th>
<th>Glass</th>
<th>Brick</th>
<th>Gypsum board</th>
<th>SIP Panels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (Kg/m³)</td>
<td>1.225</td>
<td>2520</td>
<td>1920</td>
<td>800</td>
<td>113.402</td>
</tr>
<tr>
<td>Specific Heat (J/Kg-K)</td>
<td>1006.43</td>
<td>880</td>
<td>790</td>
<td>1090</td>
<td>1.78</td>
</tr>
<tr>
<td>Thermal</td>
<td>0.0242</td>
<td>0.937</td>
<td>0.89</td>
<td>0.16</td>
<td>0.0057</td>
</tr>
</tbody>
</table>
### Table 4.2: Optical properties of low emission glass [30]

<table>
<thead>
<tr>
<th>Boundary</th>
<th>Absorptivity</th>
<th>Transmissivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Visible</td>
<td>0.71</td>
<td>Direct Visible</td>
</tr>
<tr>
<td>Direct IR</td>
<td>0.81</td>
<td>Direct IR</td>
</tr>
<tr>
<td>Diffuse Hemispherical</td>
<td>0.77</td>
<td>Diffuse Hemispherical</td>
</tr>
</tbody>
</table>

### 4.3 Boundary Conditions

The boundary conditions used in the simulation are constant temperature boundary conditions for absorber wall, glass surface and brick wall. The Boundary conditions are mentioned in the table below:

#### Table 4.3: Boundary conditions:

<table>
<thead>
<tr>
<th>Boundary</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber wall</td>
<td>Constant temperature</td>
</tr>
<tr>
<td>Velocity inlet</td>
<td>Velocity</td>
</tr>
<tr>
<td>East brick wall</td>
<td>Constant temperature</td>
</tr>
<tr>
<td>East glass wall</td>
<td>Constant temperature</td>
</tr>
<tr>
<td>Upper Inter brick wall</td>
<td>Adiabatic wall</td>
</tr>
<tr>
<td>Lower Inter Brick wall</td>
<td>Adiabatic wall</td>
</tr>
<tr>
<td>South glass wall</td>
<td>Constant temperature</td>
</tr>
<tr>
<td>South brick wall</td>
<td>Constant temperature</td>
</tr>
<tr>
<td>West Glass wall</td>
<td>Constant Temperature</td>
</tr>
<tr>
<td>West Brick wall</td>
<td>Constant temperature</td>
</tr>
<tr>
<td>Roof</td>
<td>Adiabatic wall</td>
</tr>
<tr>
<td>Pressure outlet</td>
<td>Pressure</td>
</tr>
<tr>
<td>Top wall</td>
<td>Adiabatic wall</td>
</tr>
</tbody>
</table>

The brick wall boundaries are considered as opaque walls. The glass walls are considered as semi-transparent walls and the optical properties are supplied from the data requested from manufacturer. For velocity inlet, measured values for velocity are
supplied and the initial pressure/subsonic pressure is considered as zero. For pressure outlet, the static pressure obtained from the weather station is supplied. For all boundaries backflow temperature is considered as 300 K.

4.4 Calculated Dimensionless Numbers

The dimensions of the solar chimney are: 14’2” X 6’11” X 7’4”

Longitude: 97°7’58” W

Latitude: 33°12’53” N

Reynolds No. (Re): \( \frac{UL}{\gamma} = 3577.06 \)

Re< 2000 ............ Laminar flow

Re> 4000.............. Turbulent flow

Raleigh No. (Ra): \( 6.79 \times 10^{10} \)

\( 10^4 < \text{Ra} < 10^9 \) ...........laminar flow

Ra> \( 10^9 \) ...............turbulent flow

Grashoff Number, (Gr): \( 1.76 \times 10^6 \)

\( 10^8 < \text{Gr} < 10^9 \) ........ turbulent flow
CHAPTER 5
VALIDATION

The experiments at the solar chimney were carried out to validate the simulation. Four days were selected 29th April, 30th April, 1st May and 2nd May 2013. The temperatures for external surfaces of the chimney were measured at hourly basis from 10:00 AM to 4:00 PM in the evening. To measure the outside surface temperatures, thermocouples were used, the type of thermocouple was K type. To measure the inside air temperature near surface, TMC20-HD temperature sensor from Onset were used. The inlet velocity at the chimney Domain inlet was measured with the help of T-DCI-F900-L-P air velocity sensor from Onset.

Four air temperature sensors were installed. One temperature surface was installed at east wall, one at west wall, one at south wall and the last one at the absorber wall. One air velocity sensor was installed at the inlet of the chimney, one air velocity sensor was installed at outlet of chimney, one at south wall and last one at absorber wall. The sensors were connected to the HOBO data node of ZW series. The data nodes were 4 channel data nodes. The total number was sensors used were 8 i.e. 4 temperature sensors and 4 air velocity sensors. And ultimately these sensors were connected to data nodes, and the data nodes were connected to HOBO DATA RECEIVER (ZW-RCVR).

HOBOware PRO software was used to collect the data from computer. The air velocity sensor is capable to measure velocity from 0 to 10 m/s. The temperature sensor has capacity to measure from -40°C to 100°C in air. The temperature sensor has copper plated sensor tip, which senses the temperature.
The HOBO data receiver receives the data transmitted by HOBO data nodes and uploads the data to computer to which the receiver is connected. To make the data collection active, there is need of creation of a wireless network which includes the HOBO data receiver, the data nodes and all the connected sensors. Once the wireless network is created, all data is uploaded as per the command supplied to the receiver. Here, the data was collected per minute and 24 hours but for the calculation purpose time of 10:00 AM to 4:00 PM was considered as solar energy is available at only day time.

Figure 5.1: East wall sensors

Figure 5.2: South wall sensors
Figure 5.3: West wall sensors

Figure 5.4: Absorber wall sensors

In Fig. 5.2 and 5.4, the sensor at left is the air velocity sensor and the sensor at right is temperature sensor.
6.1 Experimental Results

The experiments were carried on selected 4 days in month of April and May, the dates are 04/29/2013, 04/30/2013, 05/01/2013 & 05/02/2013. Here, four sensors are used to measure the air temperature near the surface. Sensor 1 is attached to East glass wall, sensor 2 is attached to South glass wall, sensor 3 is attached to West glass wall and sensor 4 is attached to Absorber wall. The results for 29th April for the measured data from sensors from 10:00 AM to 4:00 PM for internal surface air temperature of glass walls and absorber wall are:

![Figure 6.1: Temperature on 04/29/2013](image)

The y-axis shows the temperature in degrees celcius and the x-axis shows the total number of samples of recordings recorded by the data receiver from 10:00 AM to 4:00 PM.

The consequent temperatures for 04/30/2013, 05/01/2013 and 05/02/2013 are recorded as follows
The air velocity is the main component for the simulation and so air velocity was measured at four points in the domain, using four air velocity sensors. Air sensor 1 was installed at solar chimney inlet, air velocity sensor 2 was installed at south wall, air
sensor 3 was installed at Absorber wall and air sensor 4 was installed at solar chimney outlet. The air sensor 4 at outlet was installed at 19 cm below the solar chimney roof. This was done pertaining to the fan fixture accessory fitted at the outlet. The x-axis is the number of samples recorded by HOBO data receiver from 10:00 AM to 4:00 PM on a particular day and y-axis is the velocity in meters per second.

The air velocity sensor measurement data for all four sensors for four days is as follows:

![Figure 6.5: Air velocity for 04/29/2013](image1)

![Figure 6.6: Air velocity on 04/30/2013](image2)
The outside temperatures of the east, west and south glass walls and brick walls were measured with the help of K type thermocouple and multi-meter. The data was recorded from 10:00 AM to 4:00 PM manually. The measured temperatures are recorded in the tables below:

Table 6.1: Temperature of outside surfaces (measured) Case-1

<table>
<thead>
<tr>
<th>Surface</th>
<th>10:00 AM</th>
<th>11:00 AM</th>
<th>12:00 PM</th>
<th>1:00 PM</th>
<th>2:00 PM</th>
<th>3:00 PM</th>
<th>4:00 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>East glass</td>
<td>55°C</td>
<td>60°C</td>
<td>40.2°C</td>
<td>34.2°C</td>
<td>34.2°C</td>
<td>33°C</td>
<td>33°C</td>
</tr>
<tr>
<td>South glass</td>
<td>36°C</td>
<td>38°C</td>
<td>33.8°C</td>
<td>36.4°C</td>
<td>37.0°C</td>
<td>38.1°C</td>
<td>37°C</td>
</tr>
<tr>
<td>West glass</td>
<td>28°C</td>
<td>30°C</td>
<td>29.8°C</td>
<td>31.2°C</td>
<td>31.2°C</td>
<td>33.0°C</td>
<td>45.0°C</td>
</tr>
<tr>
<td>East Brick</td>
<td>25.0°C</td>
<td>27°C</td>
<td>28.1°C</td>
<td>29.1°C</td>
<td>29.0°C</td>
<td>28.0°C</td>
<td>27.0°C</td>
</tr>
<tr>
<td>South brick</td>
<td>24.0°C</td>
<td>27.0°C</td>
<td>29.5°C</td>
<td>30.5°C</td>
<td>31.5°C</td>
<td>30.5°C</td>
<td>30.0°C</td>
</tr>
<tr>
<td>West brick</td>
<td>24.0°C</td>
<td>27.0°C</td>
<td>27.6°C</td>
<td>29.1°C</td>
<td>31.5°C</td>
<td>31.5°C</td>
<td>31.5°C</td>
</tr>
</tbody>
</table>
Table 6.2: Temperature of outside surfaces (measured) Case 2

<table>
<thead>
<tr>
<th>Surface</th>
<th>10:00 AM</th>
<th>11:00 AM</th>
<th>12:00 PM</th>
<th>1:00 PM</th>
<th>2:00 PM</th>
<th>3:00 PM</th>
<th>4:00 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>East glass</td>
<td>45.2°C</td>
<td>41.1°C</td>
<td>35.0°C</td>
<td>32.3°C</td>
<td>27.4°C</td>
<td>27.2°C</td>
<td>27.2°C</td>
</tr>
<tr>
<td>South glass</td>
<td>26.0°C</td>
<td>31.7°C</td>
<td>32.3°C</td>
<td>34.3°C</td>
<td>31.7°C</td>
<td>35.5°C</td>
<td>32.7°C</td>
</tr>
<tr>
<td>West glass</td>
<td>24.0°C</td>
<td>27.0°C</td>
<td>28.1°C</td>
<td>30.00°C</td>
<td>30.4°C</td>
<td>40.1°C</td>
<td>49.4°C</td>
</tr>
<tr>
<td>East Brick</td>
<td>22.2°C</td>
<td>23.9°C</td>
<td>25.2°C</td>
<td>26.3°C</td>
<td>27.4°C</td>
<td>28.2°C</td>
<td>28.2°C</td>
</tr>
<tr>
<td>South brick</td>
<td>22.0°C</td>
<td>24.0°C</td>
<td>27.2°C</td>
<td>29.3°C</td>
<td>29.4°C</td>
<td>31.7°C</td>
<td>29.2°C</td>
</tr>
<tr>
<td>West brick</td>
<td>21.6°C</td>
<td>23.6°C</td>
<td>24.0°C</td>
<td>25.7°C</td>
<td>28.0°C</td>
<td>28.4°C</td>
<td>29.2°C</td>
</tr>
</tbody>
</table>

Table 6.3: Temperature of outside temperature (measured) Case 3

<table>
<thead>
<tr>
<th>Surface</th>
<th>10:00 AM</th>
<th>11:00 AM</th>
<th>12:00 PM</th>
<th>1:00 PM</th>
<th>2:00 PM</th>
<th>3:00 PM</th>
<th>4:00 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>East glass</td>
<td>27.3°C</td>
<td>29.1°C</td>
<td>31.8°C</td>
<td>34.2°C</td>
<td>32.8°C</td>
<td>31.6°C</td>
<td>31.6°C</td>
</tr>
<tr>
<td>South glass</td>
<td>27.4°C</td>
<td>30.6°C</td>
<td>33.1°C</td>
<td>36.8°C</td>
<td>36.5°C</td>
<td>37.5°C</td>
<td>36.8°C</td>
</tr>
<tr>
<td>West glass</td>
<td>28.8°C</td>
<td>30.2°C</td>
<td>30.3°C</td>
<td>30.9°C</td>
<td>32.6°C</td>
<td>38.2°C</td>
<td>51.4°C</td>
</tr>
<tr>
<td>East Brick</td>
<td>22.6°C</td>
<td>24.3°C</td>
<td>25.4°C</td>
<td>27.6°C</td>
<td>27.4°C</td>
<td>30.6°C</td>
<td>30.5°C</td>
</tr>
<tr>
<td>South brick</td>
<td>23.4°C</td>
<td>24.7°C</td>
<td>27.9°C</td>
<td>31.5°C</td>
<td>30.5°C</td>
<td>33.3°C</td>
<td>32.1°C</td>
</tr>
<tr>
<td>West brick</td>
<td>23.1°C</td>
<td>24.5°C</td>
<td>25.2°C</td>
<td>27.1°C</td>
<td>28.2°C</td>
<td>30.6°C</td>
<td>30.6°C</td>
</tr>
</tbody>
</table>

Table 6.4: Temperature of outside surfaces (measured) Case 4

<table>
<thead>
<tr>
<th>Surface</th>
<th>10:00 AM</th>
<th>11:00 AM</th>
<th>12:00 PM</th>
<th>1:00 PM</th>
<th>2:00 PM</th>
<th>3:00 PM</th>
<th>4:00 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>East glass</td>
<td>11.0°C</td>
<td>13.2°C</td>
<td>13.2°C</td>
<td>13.0°C</td>
<td>12.6°C</td>
<td>10.8°C</td>
<td>10.0°C</td>
</tr>
<tr>
<td>South glass</td>
<td>13.2°C</td>
<td>15.8°C</td>
<td>15.0°C</td>
<td>13.2°C</td>
<td>12.8°C</td>
<td>12.8°C</td>
<td>12.0°C</td>
</tr>
<tr>
<td>West glass</td>
<td>13.0°C</td>
<td>14.1°C</td>
<td>14.1°C</td>
<td>14.1°C</td>
<td>12.2°C</td>
<td>10.2°C</td>
<td>11.0°C</td>
</tr>
<tr>
<td>East Brick</td>
<td>11.7°C</td>
<td>11.7°C</td>
<td>11.6°C</td>
<td>11.6°C</td>
<td>11.5°C</td>
<td>11.5°C</td>
<td>11.5°C</td>
</tr>
<tr>
<td>South brick</td>
<td>12.5°C</td>
<td>12.7°C</td>
<td>12.7°C</td>
<td>12.5°C</td>
<td>12.6°C</td>
<td>11.1°C</td>
<td>11.1°C</td>
</tr>
<tr>
<td>West brick</td>
<td>14.0°C</td>
<td>14.6°C</td>
<td>14.3°C</td>
<td>14.2°C</td>
<td>14.4°C</td>
<td>11.8°C</td>
<td>11.8°C</td>
</tr>
</tbody>
</table>
The solar radiation are measured by Kipp and Zonnen CM 11 pyranometer and this data is recorded by Building monitoring system provided by Schneider Electric, the name of the software is TAC Vista. The solar radiation is recorded monthly for April the data was 515.64 W/m² and for May it was recorded as 118.20 W/m².

6.2 Simulation Results

For the simulation, as per the calculation of dimensionless numbers like Rayleigh Number, Grashoff number, etc. It was found that the flow is transitional flow inside solar chimney. To model the solar chimney, Laminar energy equations were solved and constant temperature boundary conditions were applied. Four days were selected for measurements and simulation. From here onwards, each day will be considered as a separate case for nomenclature purpose, for example: 04/29/2013 = Case 1, 04/30/2013= Case 2, 05/01/2013= Case 3 and 05/02/2013= Case 4. For the first models, fine mesh is considered with size 8.599e-004 X 8.599e-002 m. The mesh consisted of 29903 nodes and 152938 elements.

The input parameters for the simulation are:

**Table 6.5: Input pressure**

<table>
<thead>
<tr>
<th>Inlet pressure (pascal)</th>
<th>Outlet pressure</th>
<th>Difference in pressure</th>
<th>date</th>
</tr>
</thead>
<tbody>
<tr>
<td>99711.8</td>
<td>101013.7</td>
<td>1301.9</td>
<td>04/29/2013= case 1</td>
</tr>
<tr>
<td>97298.58</td>
<td>100999.38</td>
<td>3700.8</td>
<td>04/30/2013= case 2</td>
</tr>
<tr>
<td>97631.88</td>
<td>100982.11</td>
<td>3350.23</td>
<td>05/01/2013= case 3</td>
</tr>
<tr>
<td>98965.11</td>
<td>102404.39</td>
<td>3439.28</td>
<td>05/02/2013= case 4</td>
</tr>
</tbody>
</table>

**Table 6.6: Input temperature at each boundary**

<table>
<thead>
<tr>
<th>surface</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>East glass wall</td>
<td>301.5</td>
<td>300.3</td>
<td>301.24</td>
<td>288.70</td>
</tr>
<tr>
<td>Component</td>
<td>Case 1</td>
<td>Case 2</td>
<td>Case 3</td>
<td>Case 4</td>
</tr>
<tr>
<td>--------------------</td>
<td>--------------</td>
<td>--------------</td>
<td>--------------</td>
<td>--------------</td>
</tr>
<tr>
<td>South glass wll</td>
<td>305.38</td>
<td>304</td>
<td>304.1</td>
<td>288.73</td>
</tr>
<tr>
<td>West wall</td>
<td>302.75</td>
<td>302.37</td>
<td>302.62</td>
<td>286.23</td>
</tr>
<tr>
<td>Absorber wall</td>
<td>298.4</td>
<td>298</td>
<td>297.7</td>
<td>290.32</td>
</tr>
<tr>
<td>East brick</td>
<td>298.4</td>
<td>298</td>
<td>297.7</td>
<td>290.32</td>
</tr>
<tr>
<td>South brick</td>
<td>298.4</td>
<td>298</td>
<td>297.7</td>
<td>290.32</td>
</tr>
<tr>
<td>West brick</td>
<td>298.4</td>
<td>298</td>
<td>297.7</td>
<td>290.32</td>
</tr>
</tbody>
</table>

**Table 6.7: Input ambient temperature**

<table>
<thead>
<tr>
<th>Cases</th>
<th>Temperature (ambient) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>291.65</td>
</tr>
<tr>
<td>Case 2</td>
<td>291.25</td>
</tr>
<tr>
<td>Case 3</td>
<td>291.88</td>
</tr>
<tr>
<td>Case 4</td>
<td>281.33</td>
</tr>
</tbody>
</table>

The simulation is pressure based and steady state. Gravity acts downwards. For pressure-velocity coupling, SIMPLE scheme has been used. The spatial discretization for gradient is least square cell based, for pressure it is body force weighted, for momentum and energy-second order upwind scheme is used. Solar load model has been implemented to study the effect of solar radiations on the solar chimney flow domain. For the solar load model, Fair weather conditions were considered in the FLUENT and sun-shine factor of 0.7 was applied. The sun-shine factor is the constant which enable solar radiation to be considered in the simulation, the value of 1 means maximum solar radiation incident i.e. 1000 W/m² and the value of 0 means 0 w/m² radiations incident. Mesh orientation for solar load model is North (0,1,0) and East (0,0,1). Lattitude of 33.21484° and Longitudes of -97.13307° are used to consider real location in the solar load model. The time zone of GMT -5 is considered.

The temperature contours at glass walls and absorber wall is presented below.
Figure 6.9: Case 1, Absorber wall temperature contour

Figure 6.10: Case 2, absorber wall temp. contour

Figure 6.11: Case 3, Absorber wall temperature contour

Figure 6.12: Case 4, Absorber wall temp. contour
East glass wall:

Figure 6.13: Case 1, east glass temp. contour

Figure 6.14: Case 2, East glass temp. contour

Figure 6.15: Case 3: east glass temp. contour

Figure 6.16: Case 4: east glass temp. contour
South glass wall:

Figure 6.17: case 1, south glass temp. contour

Figure 6.18: case 2, south glass temp. contour

Figure 6.19: case 3, south wall temp. contour

Figure 6.20: case 4, south glass temp. contour
Figure 6.21: case 1, west glass temp. contour

Figure 6.22: case 2, west glass temp. contour

Figure 6.23: case 3, west glass temp. contour

Figure 6.24: case 4, west glass temp. contour
Figure 6.25: Case 1, east brick temp. contour

Figure 6.26: case 2, east brick temp. contour

Figure 6.27: Case 3, east brick temp. contour

Figure 6.28: case 4, east brick temp. contour
Figure 6.29: case 1, south brick temp. contour

Figure 6.30: case 2, south brick temp. contour

Figure 6.31: case 3, south brick temp. contour

Figure 6.32: case 4, south brick temp. contour
Figure 6.33: case 1, west brick temp. contour

Figure 6.34: case 2, west brick temp. contour

Figure 6.35: case 3, west brick temp. contour

Figure 6.36: case 4, west brick temp. contour
The velocity profile at the outlet of chimney for all four cases:

Figure 6.37: case 1, outlet velocity profile
Figure 6.38: case 2, outlet velocity profile
Figure 6.39: case 3, outlet velocity profile
Figure 6.40: case 4, outlet velocity profile

The XY plot on the Absorber wall shows the increase in temperature with height, Y-axis shows temperature and X-axis shows position, the left side is top and right edge is the bottom of the chimney.
Figure 6.41: case 1, absorber plate X-Y plot

Figure 6.42: case 2, absorber plate X-Y plot

Figure 6.43: case 3, absorber plate X-Y Plot

Figure 6.44: case 4, absorber plate X-Y plot

The XY plot on south glass wall shows constant temperature throughout surface on particular day. The Y-axis shows temperature in kelvin and X-axis shows position, the left side of the graph is top of chimney and right most side of graph is distance until 6’ from top of chimney. The plot can be seen as below:
Figure 6.45: case 1, south glass X-Y plot

Figure 6.46: case 2, south glass X-Y plot

Figure 6.47: case 3, south glass X-Y plot

Figure 6.48: case 4, south glass X-Y plot

The stream lines show that good uniform flow without backflow, the streamlines for all four cases are as below:
When the vectors were plotted for all four cases, they show conformity to uniform flow. The air enters at bottom and flow out from outlet as clearly visible in vectors:
The mass imbalance was observed from the results of simulation to be very low.

The simulation results are:
### Table 6.8: Simulated results for Mass flow rate:

<table>
<thead>
<tr>
<th>Case</th>
<th>Boundary condition</th>
<th>Mass flow rate (Kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Pressure outlet</td>
<td>-0.11506</td>
</tr>
<tr>
<td></td>
<td>Velocity inlet</td>
<td>0.1142</td>
</tr>
<tr>
<td>Case 2</td>
<td>Pressure outlet</td>
<td>-0.0969</td>
</tr>
<tr>
<td></td>
<td>Velocity inlet</td>
<td>0.0979</td>
</tr>
<tr>
<td>Case 3</td>
<td>Pressure outlet</td>
<td>-0.1470</td>
</tr>
<tr>
<td></td>
<td>Velocity inlet</td>
<td>0.1468</td>
</tr>
<tr>
<td>Case 4</td>
<td>Pressure outlet</td>
<td>0.1132</td>
</tr>
<tr>
<td></td>
<td>Velocity inlet</td>
<td>0.1142</td>
</tr>
</tbody>
</table>

### Table 6.9: Simulated results for Volumetric flow rate

<table>
<thead>
<tr>
<th>Case</th>
<th>Boundary condition</th>
<th>Volumetric flow rate (m³/s)</th>
<th>Volumetric flow rate (m³/h)</th>
<th>Volumetric flow rate in CFM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Pressure outlet</td>
<td>-0.0939</td>
<td>338</td>
<td>199</td>
</tr>
<tr>
<td></td>
<td>Velocity inlet</td>
<td>0.0932</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 2</td>
<td>Pressure outlet</td>
<td>-0.0791</td>
<td>285</td>
<td>168</td>
</tr>
<tr>
<td></td>
<td>Velocity inlet</td>
<td>0.0799</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 3</td>
<td>Pressure outlet</td>
<td>-0.1200</td>
<td>432</td>
<td>254</td>
</tr>
<tr>
<td></td>
<td>Velocity inlet</td>
<td>0.1199</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 4</td>
<td>Pressure outlet</td>
<td>-0.0924</td>
<td>333</td>
<td>196</td>
</tr>
<tr>
<td></td>
<td>Velocity inlet</td>
<td>0.0932</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 6.10: Comparison between experimental and simulated results of velocity with laminar model

<table>
<thead>
<tr>
<th>Case</th>
<th>Inlet velocity (m/s)</th>
<th>Measured velocity (outlet) [m/s]</th>
<th>Simulated velocity (outlet) [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.07</td>
<td>0.2139</td>
<td>0.249</td>
</tr>
<tr>
<td>2</td>
<td>0.06</td>
<td>0.2155</td>
<td>0.168</td>
</tr>
<tr>
<td>3</td>
<td>0.09</td>
<td>0.1109</td>
<td>0.31</td>
</tr>
<tr>
<td>4</td>
<td>0.07</td>
<td>0.1855</td>
<td>0.28</td>
</tr>
</tbody>
</table>

### Table 6.11: Results of simulation for glass wall temperatures with laminar model

<table>
<thead>
<tr>
<th>surface</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>East glass</td>
<td>304.72 K</td>
<td>303.57 K</td>
<td>304.43 K</td>
<td>292.34 K</td>
</tr>
<tr>
<td>South glass</td>
<td>312.30 K</td>
<td>310.98 K</td>
<td>309.02 K</td>
<td>295.95 K</td>
</tr>
<tr>
<td>West glass</td>
<td>307.18 K</td>
<td>306.81 K</td>
<td>306.44 K</td>
<td>291.21 K</td>
</tr>
</tbody>
</table>

### Table 6.12: Results of simulation for wall temperatures with laminar model
The solar load data for transmitted visible solar radiations and transmitted Infra-Red solar radiations through the semi-transparent boundaries i.e. the low emission glass walls are presented below in tabular form from CFD simulation:

<table>
<thead>
<tr>
<th>Surface</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber wall</td>
<td>305.88</td>
<td>305.69</td>
<td>304.19</td>
<td>300.93</td>
</tr>
<tr>
<td>East brick wall</td>
<td>303.31</td>
<td>303.08</td>
<td>302.20</td>
<td>298.01</td>
</tr>
<tr>
<td>South brick wall</td>
<td>303.21</td>
<td>302.97</td>
<td>302.19</td>
<td>297.68</td>
</tr>
<tr>
<td>West glass wall</td>
<td>303.02</td>
<td>302.79</td>
<td>302.07</td>
<td>297.70</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Transmitted visible (W/m²)</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Transmitted IR (W/m²)</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>East glass</td>
<td>13.94</td>
<td>13.94</td>
<td>13.94</td>
<td>14.05</td>
<td>East glass</td>
<td>0.02</td>
<td>0.02</td>
<td>0.008</td>
<td>0.01</td>
</tr>
<tr>
<td>South glass</td>
<td>35.00</td>
<td>35.00</td>
<td>23.65</td>
<td>33.48</td>
<td>South glass</td>
<td>7.59</td>
<td>7.59</td>
<td>3.07</td>
<td>6.95</td>
</tr>
<tr>
<td>West glass</td>
<td>19.75</td>
<td>19.75</td>
<td>17.12</td>
<td>19.93</td>
<td>West glass</td>
<td>1.89</td>
<td>1.89</td>
<td>0.81</td>
<td>1.91</td>
</tr>
</tbody>
</table>

6.3 Mesh Variations

The mesh variation study was done by modeling solar chimney with three kinds of mesh viz. coarse, medium and fine as defined in the ANSYS MESHING software. For the coarse mesh 1652 nodes and 7412 elements were comprised for the geometry and the mesh size was 2.9359e-002 X 0.293590 m. For medium mesh, the geometry consisted of 8702 nodes and 42213 elements and the mesh size was 1.468e-003 X 0.14680 m. The fine mesh consisted of 29903 nodes and 152938 elements and mesh size of 8.599e-004 X 8.599e-002 m. The models were simulated for all similar inputs as done for the results above, iterations were also same i.e. 750 iterations for steady state simulation. The results of velocity at a particular point at outlet were the sensor was exactly mounted with coordinates (0.3424, 0.04,-0.04) are presented for all three kinds of meshes and all four cases:
Table 6.14: Mesh variation data

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>0.37 m/s</td>
<td>0.31 m/s</td>
<td>0.43 m/s</td>
<td>0.27 m/s</td>
</tr>
<tr>
<td>Medium</td>
<td>0.256 m/s</td>
<td>0.32 m/s</td>
<td>0.30 m/s</td>
<td>0.26 m/s</td>
</tr>
<tr>
<td>Fine</td>
<td>0.249 m/s</td>
<td>0.168 m/s</td>
<td>0.31 m/s</td>
<td>0.28 m/s</td>
</tr>
</tbody>
</table>

The mesh was varied for case 2 and various sizes were simulated the simulation showed a linear trend in the medium sized meshes tried and the fine mesh simulated.

The simulation values for output velocities for these mesh sizes are shown below:

Table 6.15: different mesh sizes simulation for medium mesh and comparison with fine mesh size

<table>
<thead>
<tr>
<th>Mesh size</th>
<th>Output velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium 0.001468 X 0.1468 m</td>
<td>0.32</td>
</tr>
<tr>
<td>Medium 0.001800 X 0.1800 m</td>
<td>0.155</td>
</tr>
<tr>
<td>Medium 0.002532 X 0.2532 m</td>
<td>0.1755</td>
</tr>
<tr>
<td>Fine 0.0008954 X 0.08954 m</td>
<td>0.168</td>
</tr>
</tbody>
</table>

For case 1, different simulations were run for different iterations and has linear output velocities and it can be concluded that mesh is in conformity with independence.

The table with these values is shown below:

Table 6.16: Simulation results with different iterations

<table>
<thead>
<tr>
<th>Iterations</th>
<th>Output velocity, (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>750</td>
<td>0.249</td>
</tr>
<tr>
<td>1000</td>
<td>0.244</td>
</tr>
<tr>
<td>1250</td>
<td>0.254</td>
</tr>
</tbody>
</table>

6.4 Turbulence Model

To analyze the results of velocity at out-let, realizable k-ε model. The kinetic energy was taken as 1 m/s² and the dissipation rate was taken as 0.3 m²/s². The inputs for the simulation were same as the laminar model inputs as in table 6.5, 6.6, 6.7. 750 iterations were considered for the simulation and the solution converged for around 326
iterations for all four cases considered. The out-let velocities from the simulation show accuracy than the velocities recorded from the laminar model. The results for turbulence models in terms of velocities is as below:

Table 6.17: Comparison between experimental and simulated values of velocity for turbulence model

<table>
<thead>
<tr>
<th>cases</th>
<th>Velocity at outlet (turbulence model) m/s</th>
<th>Measured values for velocity, m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.236</td>
<td>0.213</td>
</tr>
<tr>
<td>2</td>
<td>0.225</td>
<td>0.215</td>
</tr>
<tr>
<td>3</td>
<td>0.311</td>
<td>0.110</td>
</tr>
<tr>
<td>4</td>
<td>0.26</td>
<td>0.185</td>
</tr>
</tbody>
</table>

6.5 Discussion of Results

The experimental results of the measurement of internal surface air temperatures for the east, south and west glass walls and the absorber walls as seen from the fig. 6.1 to fig. 6.4 shows that for case 1 i.e. for 04/29/2013 the east glass wall surface air temperature is highest in the beginning of the experiment i.e. at 10:00 AM in the morning but it decreases by the end of the day until 4:00 PM. The South glass surface temperature rises as the sun approaches towards noon and remains high with little decrease towards the end of the experiment. The west glass surface air temperature remains low until mid-day at 12:00 PM and after that starts increasing and has the highest temperature by the end of experiment. The absorber wall surface temperature increases as the day approaches but it is usually lower than all the glass wall temperatures throughout the experiment. The south glass wall temperature for internal surface air temperature is highest among all other surfaces, though at the end of the experiment west glass wall has highest surface air temperature. This pattern of temperatures is followed for each case i.e. case 1, case 2 and case 3, but for case 4 the
pattern changes. This change can be attributed to the colder weather observed on that particular day. For case 4, it was observed from the experimental results that absorber wall temperature is highest on this day, then the south glass wall has second highest temperature and then the west glass wall. For all the temperatures on this day, the temperatures rise until afternoon and then start decreasing below ambient temperature. Case 1 i.e. the day of 04/29/2013 was observed to be the hottest day from the experiments and the case 4 i.e. 05/02/2013 was found to be the coldest day among all cases.

The air velocity is the main parameter in the solar chimney, responsible for the ventilation rate of the chimney. From the experiments which were conducted on all four cases, it is evident that the velocity at the outlet of the chimney is highest and velocity at the south wall is the lowest in the solar chimney flow domain. The sensor was installed on the diffusor assembly of the exhaust fan fixture provided at outlet of the chimney. The location of sensor was 19 cm below the chimney roof. All the outlet velocities are measured at this point. The measured values of outlet and inlet velocities are as follows:

<table>
<thead>
<tr>
<th>cases</th>
<th>Inlet velocity (m/s)</th>
<th>Outlet velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.07</td>
<td>0.2139</td>
</tr>
<tr>
<td>2</td>
<td>0.06</td>
<td>0.2155</td>
</tr>
<tr>
<td>3</td>
<td>0.09</td>
<td>0.1109</td>
</tr>
<tr>
<td>4</td>
<td>0.07</td>
<td>0.1855</td>
</tr>
</tbody>
</table>

From the experiments, it is observed that the air flows through the chimney inlet then it approaches towards the outlet of the chimney due to the decrease in density. As
lighter air approaches altitude, the decrease in density of air due to heat gain from the incident solar radiation transmitted through the glass walls causes air to pass upwards. During this passage, the air flows aligning itself to the surface of absorber wall. This phenomenon can be understood by the velocity measurement values recorded at chimney inlet, south wall, absorber wall and chimney outlet. This data is arranged in tabular form as below for all four cases:

![Figure 6.57: case 1, Flow of air velocity](image1)

![Figure 6.58: case 2, Flow of air velocity](image2)
In figures 6.55 to 6.58 the x-axis represents individual sensors like the point one is sensor 1 installed at chimney in-let, point 2 is sensor 2 installed at south wall, point 3 is sensor 3 installed absorber wall and point 4 is sensor 4 installed at chimney outlet. The y-axis represents the value of velocity in meters per second. From these graphs it is evident that the air enters at in-let and then its flows to the chimney out-let aligning itself to the absorber wall. This phenomenon proves the chimney flow to be uniform.
6.5.1 Temperature Variations

The measurement of the outside surface temperatures of the glass walls and brick walls was done from 10:00 AM to 4:00 PM on selected days with the help of K-type thermocouples. The results follow the same pattern as the internal surface air temperatures. The south glass wall has the highest temperature among all surfaces and also among glass surfaces. The south brick wall has highest temperature among all brick surfaces. The west glass wall heats up as sun tends towards the setting time, so does the west brick wall. For simulation, the average value of measured internal surface air temperature values of all surfaces from 1:00 PM to 4:00 PM were supplied as input. Then the simulation result was compared with the measured outlet surface temperatures from the time slot of 1:00 PM to 4:00 PM for all selected cases. The measured outlet surface temperatures for selected time slot for glass and brick surfaces are:

Table 6.19: Experimental values of measurement of temperature at outside surface of glass wall surfaces

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>East glass</td>
<td>306.6</td>
<td>301.52</td>
<td>305.55</td>
<td>284.6</td>
</tr>
<tr>
<td>South glass</td>
<td>310.12</td>
<td>306.55</td>
<td>309.9</td>
<td>285.7</td>
</tr>
<tr>
<td>West glass</td>
<td>308.1</td>
<td>310.57</td>
<td>310.27</td>
<td>284.87</td>
</tr>
</tbody>
</table>

Table 6.20: Experimental values of measurement of temperature at outside surface of brick wall surfaces

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber wall</td>
<td>298.4</td>
<td>298</td>
<td>297.7</td>
<td>290.32</td>
</tr>
<tr>
<td>East brick</td>
<td>301.27</td>
<td>300.52</td>
<td>302.02</td>
<td>284.12</td>
</tr>
<tr>
<td>South brick</td>
<td>303.62</td>
<td>302.9</td>
<td>304.85</td>
<td>288</td>
</tr>
<tr>
<td>West brick</td>
<td>303.9</td>
<td>300.82</td>
<td>302.12</td>
<td>286.05</td>
</tr>
</tbody>
</table>
The simulation results and experimental results show good agreement for the outside surface temperatures of both the glass wall surfaces and brick wall surfaces. For the glass wall surface the percentage difference between simulation and experimental values is less than 3.5 %. The negative percentage difference means simulation result is less than experimental result and positive percentage difference means simulation result is higher than experimental result. The percentage difference between simulation and experimental values of brick wall also are in good agreement. The percentage difference is less than or equal to 4.5 % in maximum case. The graph for the percentage difference values for glass wall and brick wall surfaces are given below:

Figure 6.61: Percentage difference in temperature for glass wall
6.5.2 Air Velocity Variations

When the solar chimney model was simulated using the laminar energy equations, there was large difference in the simulated and experimental values. This large difference in the simulated values and experimental values can be because of wind effect. Although the wind effect was neglected during experiments and also during simulations, the possibility of intervention due to wind in the experiments cannot be denied. Even though the building can be considered as a air tight building, there is a possibility of infiltration of air from outside. The graph of percentage difference between experimental and simulation results is given below:
Figure 6.63: percentage difference for laminar flow

In fig. 6.61, the x-axis shows for cases each number corresponds to individual case and the y-axis shows the difference in percentage between experimental and simulated values.

To check the values of velocity at the chimney out-let and to see if the values from laminar flow energy equation simulation are true or not, Realizable k- epsilon turbulent model was used. The simulation gave good values than the laminar energy equations. The graph of the percentage difference between the simulation results and experimental results is as given below:

Figure 6.64: percentage difference for turbulent flow
In Fig. 6.62 the x-axis corresponds to individual cases and y-axis shows the difference in percentage. The laminar flow shows reduction in velocity magnitude by 5.2% for case 1, for case 2 there is 25% increase in velocity, the result of case is similar in both cases and for last case the reduction in velocity at outlet is 7.1%.

Again, the laminar energy equation model was run. This time, the sun-shine factor was reduced to 0.56 for case 1 and 2, for case 3 and 4 the sun-shine factor was reduced to 0.13 from 0.7 before. This change was made based on data received from building monitoring system's solar radiation data. The pressure difference between outlet and in-let was kept 1000 Pascal. The new simulation results showed reduction in air velocity at outlet for case 3 and 4 by 3.2% and 7% respectively and increase in case 1 and 2 velocity by 1.6% and 10%. Comparing the new laminar simulation data to the old laminar simulation data, it was observed that new laminar simulation gave better results than old one. The outlet velocity for case 1, 3 and 4 reduced by 3.6%, 3.2% and 14.28% while the case 2 outlet velocity increased by 32.8%.

6.5.3 Pressure Variations

Pressure variation studies were done on the two cases 1 and 2. And the results are:

For case 1:

<table>
<thead>
<tr>
<th>Pressure difference between outlet and inlet (Pascal)</th>
<th>Outlet velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.249</td>
</tr>
<tr>
<td>500</td>
<td>0.248</td>
</tr>
<tr>
<td>250</td>
<td>0.263</td>
</tr>
<tr>
<td>-1000</td>
<td>0.48</td>
</tr>
<tr>
<td>-500</td>
<td>0.256</td>
</tr>
<tr>
<td>-250</td>
<td>0.211</td>
</tr>
</tbody>
</table>
For Case 2:

**Table 6.22: Comparison between pressure difference and velocity results for case 2**

<table>
<thead>
<tr>
<th>Pressure difference between outlet and inlet (Pascal)</th>
<th>Outlet velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.223</td>
</tr>
<tr>
<td>500</td>
<td>0.218</td>
</tr>
<tr>
<td>250</td>
<td>0.248</td>
</tr>
<tr>
<td>-1000</td>
<td>0.38</td>
</tr>
<tr>
<td>-500</td>
<td>0.251</td>
</tr>
<tr>
<td>-250</td>
<td>0.22</td>
</tr>
</tbody>
</table>

For Case 3:

**Table 6.23: Comparison between pressure difference and velocity results for case 3**

<table>
<thead>
<tr>
<th>Pressure difference between outlet and inlet (Pascal)</th>
<th>Outlet velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.29</td>
</tr>
<tr>
<td>500</td>
<td>0.28</td>
</tr>
<tr>
<td>250</td>
<td>0.285</td>
</tr>
<tr>
<td>-1000</td>
<td>0.32</td>
</tr>
<tr>
<td>-500</td>
<td>0.30</td>
</tr>
<tr>
<td>-250</td>
<td>0.29</td>
</tr>
</tbody>
</table>

For Case 4:

**Table 6.24: Comparison between pressure difference and velocity results for case 4**

<table>
<thead>
<tr>
<th>Pressure difference between outlet and inlet (Pascal)</th>
<th>Outlet velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.27</td>
</tr>
<tr>
<td>500</td>
<td>0.25</td>
</tr>
<tr>
<td>250</td>
<td>0.294</td>
</tr>
<tr>
<td>-1000</td>
<td>0.31</td>
</tr>
<tr>
<td>-500</td>
<td>0.29</td>
</tr>
<tr>
<td>-250</td>
<td>0.28</td>
</tr>
</tbody>
</table>

The cases 1, 2, 3 and 4 were simulated with different pressure difference values. 6 separate simulations were done, with varying the pressure values at outlet and inlet.
from positive 1000, 500 and 250 and negative 1000, 500, 250. The variations in pressure shows us that the outlet velocity is dependent of difference in pressure and as a whole velocity is also affected by pressure. The positive pressure difference occurs when the outlet pressure is bigger than the inlet pressure and the negative pressure occurs when the outlet pressure is less than the inlet pressure. For case 1 it is observed that for positive pressure difference the value remains nearly constant when the pressure difference changes from 100 to 500 but it increases by 5.7 % when the pressure difference changes to 250 Pascal. For negative pressure difference the velocity shows consistent decrease in the value. Highest value of velocity for all six simulations for this particular scenario is found to be 0.48 m/s and least was found when pressure difference was negative 250 Pascal. For case 2 also the pattern is same as that of case 1 but the least velocity all the six simulations for this case shows the minimum velocity of 0.218 at positive 500 Pascal pressure difference.

From the vectors plotted for the all four cases, it can be seen the flow is seen to be uniform. The flow enters the flow domain of this solar chimney from the inlet at the bottom and exits from the outlet at the top. There is no leakage or outflow of vectors from the flow domain. It can be interpreted from this that the geometry is water tight. After the flow enters domain, it reaches for the top by aligning itself to the absorber wall. This characteristic is evident from the fig. 6.51 to 6.54 and also supported by the velocity measurements and the streamlines data.

6.5.4 Absorber Wall Temperature

From figures 6.39 to 6.42, it is evident that the temperature of absorber wall
increases with the height if solar chimney. In the figures 6.39 to 6.42 on the x-axis left hand side represents the top position of chimney i.e. top of chimney and the right hand side represents the lower side of chimney i.e. the inlet of chimney. Even though the temperature increases with chimney height, it is conveniently less than the glass walls. This less temperature value can be attribute due to the white paint applied to the surface of absorber wall. Due to this white paint, it reflects most of the solar radiations incident on the surfaces.

6.5.5 South Glass Wall Temperature

From figures 6.4 to 6.46 it is observed that maximum temperature for all four cases considered occurs for case 1 and the least temperature occurs at case 4. The temperature of south glass wall is seen to remain constant for the particular simulation. From the measurements, it is confirmed that south glass wall has the maximum temperature among all glass surfaces. The least temperature for the south glass wall was for case 4 and that should be because of the cold weather condition on this particular day.

6.5.6 Energy Saving in terms of Cooling Load \( (h_s) \) and Fan Power Output \( (W_f) \)

The volumetric flow rate produced from the solar chimney or which is also known as ventilation rate produced from solar chimney can be used as a measure of solar chimney’s capacity to vent cooling load or in similar terms it capability to save power in terms of fan power output. It can be expressed from the following equations:

\[
W_f = \frac{Q \times \Delta P_f}{\eta_f} \tag{Equation 23}
\]
\[ \eta_f = 0.95 \text{ and } \Delta P_t = 0.25 \text{ W.G.} = 62.27 \text{ Pascal; } Q = 0.12 \text{ m}^3/\text{s} \text{ (Table 12)} \]

The calculated \( W_f = 7.85 \) Watts.

The cooling load saving can be expressed in the equation below:

\[ h_s = 1.08 X Q X dt \]
\[ dt = 20^\circ C = 68^\circ F \]

Therefore, \( h_s = 31,726.08 \text{ Btu/hr} = 9.29 \text{ Kwh} \)

6.6 Conclusion

The solar chimney studied in this investigation is different from other general solar chimneys. The solar chimneys generally employ matt black color for the absorber wall, so that maximum solar radiations incident are absorbed and surface temperature is increased. They also employ a glass wall as glazing, generally single pane clear glass. This is done to prevent heat losses from the flow domain and transmit solar radiation in the domain. By virtue of such a system density variation is observed and flow is made possible, creating maximum ventilation rate intended. In this study, the solar chimney considered has white painted absorber wall and low emission glass as glazing. The conclusions can be summarized as below:

- The temperatures of the glass walls and brick walls and absorber wall are predicted in good agreement with the experimental results. For the east glass wall minimum percentage difference between simulation and experiment results is 2.6 %, for south glass wall it is 1.4 % and for west glass it is 1.2 %. For the absorber wall the minimum percentage difference between the simulation and experimental results is 2.1 %. Here, the absorber wall temperature is over-predicted by 2.1 % by simulation
compared to the experimental results. For east brick wall the minimum percentage
difference is 0.05 %, for south brick wall it is 0.01 % and for west brick it is 0.01 %.

- The absorber wall temperature is minimum at the inlet of solar chimney and it
  increases towards the exit of solar chimney.

- The laminar flow equation simulation in FLUENT over-predict the velocity at
  outlet compared to the experimental results. The minimum percentage difference
  between simulation and experimental results is 0.144% in case 1, In case 3 the
  prediction of velocity is higher than by experimental results by 0.64 %. The realizable
  k-epsilon turbulence model was employed to check accuracy of velocity and it is evident
  that out of four cases considered for study, this type of simulation shows improved
  velocities than laminar flow in three cases. So, the turbulence model shows good results
  for 75% of cases. The minimum percentage difference for turbulence model is 4.4 %.

Again, laminar simulation was run with 1000 Pascal pressure difference at outlet and
inlet and reduced sun-shine factor to account for solar radiation data. This model
showed improvement in velocity prediction in comparison to previous laminar
simulation.

- Pressure difference between outlet of solar chimney and inlet of solar
  chimney has effect on the velocity at outlet of chimney. The simulations with pressure
  difference variation from positive 1000-250 Pascal and negative 1000-250 Pascal for
  two cases show that for case 2, the percentage difference between maximum and
  minimum velocity is 42.6%. For case 1, this percentage difference was 56%.

- The ventilation flow rate generated by this solar chimney is enough to
  ventilate a single story, two room building like Zero energy Research Lab. The
ventilation rate generated is in range of 432-285 m$^3$/h. The maximum air flow is of 432 m$^3$/h and minimum ventilation rate is 285 m$^3$/h.

- Sun-shine factor which accounts for solar radiation data in solar calculator, has an effect on solar chimney behavior. The first laminar simulation was done with high solar radiation over predicted velocity at outlet, but when the sun-shine factor is reduced to account for real recorded solar data from building Monitoring system and the laminar simulation was run again showing good results.

- Inspite of different materials used for solar chimney which are related to energy efficient buildings, the solar chimney has generated good volume of ventilation rates. This makes this study independent of materials used for solar chimney. The high ventilation rate can be also due the relatively large flow domain compared to general chimneys.

- The energy saving potential of solar chimney from the calculations is seen to be 7.86 Watts in terms of fan power output and it can be concluded that the cooling load saved by this chimney is 9.29 Kwh as per the calculations.

- The over all conclusion is that, this solar chimney’s performance is good. It generated sufficient ventilation for required habitable area.
REFERENCES


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