Sustainable Energy Technologies and Assessments xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

journal homepage: www.elsevier.com/locate/seta

Shelter energy use reduction through buoyancy-driven air flow manipulation: A numerical and experimental study

Vinit Vinayak Prabhu, Ehsan Mohseni Languri*

Department of Mechanical Engineering, Tennessee Technological University, Cookeville, TN 38505, USA

ARTICLE INFO

Keywords:
Energy
Air conditioning
Shelter
Natural heat transfer
Efficiency

ABSTRACT

The significance of reduction in energy usage of air-conditioned fabric structures, such as shelters, is huge considering the risks and the cost associated with running a generator in off-grid situations. As shelters are typically used in extreme climatic conditions, the energy usage as well as the transportation and running costs are high. The aim of this project is to modify the design of the shelter air gap to reduce the heat transfer due to buoyancy-driven flows across the shelter layers. To reduce the heat transfer, an additional layer is considered inside the air gap at various locations to suppress the natural convection heat transfer. A numerical model is developed to study the performance of the shelter under various conditions and validated by experimental data. The results of all cases are studied and the heat transfer data are reported. The temperature contours, velocity streamlines, Nusselt number, and power usage are calculated. The energy savings obtained with various air gap designs are also studied and reported. The results of this study show that improving the design of air gap by adding an additional layer can lead to significant reduction of air conditioning energy use in such shelters.

Introduction

Fabric structures such as shelters are light in weight and are widely used at the forward bases where they can be deployed quickly. Efforts have been made over the past several years to increase the energy efficiency of these shelters. An Environmental Control Unit (ECU) controls the interior temperature of the shelters and operates on a generator, which consumes a large amount of fuel, usually diesel. A continuous supply of fuel by the means of tankers is required to keep the ECU operating. This increases the risks and the costs associated with the transportation of fuel. One study shows that approximately seven gallons of fuel can be consumed to transport one gallon of fuel for use by generators [1]. Also, since the fuel is flammable in nature, proper storage is needed. Therefore, increasing the efficiency of the shelters and ECU in order to reduce the associated costs becomes important.

The heating and air conditioning via ECUs consume three-quarters of the electric energy produced by the generators [1]. Similar to any envelop, a large amount of heat is transferred across the layers of the shelter into the shelter envelop, and the ECU is responsible for removing the heat and maintaining the interior and a constant desired temperature of the shelter. A typical shelter consists of two layers with an air gap, which acts as an insulator, between the two layers. However, as there is a temperature difference across the air gap, some natural convection flows are formed inside the air gap. This natural convection flow causes heat transfer across the air gap. Also, in some cases, the radiation of the sun causes heat transfer to take place. The radiation of the sun heats up the outer layer of the shelter, which in turn radiates the interior layer. Another important cause of the reduction in efficiency is the air leakage from the shelter.

The heat transfer across the air gap must be minimized in order to reduce the energy consumption by the ECUs. This will cause a reduction in demand for the fuel required by the generator, thus, reducing the risks and costs associated with the transportation of the fuel.

The natural convection inside the enclosures has been studied and analyzed by researchers over the past few decades. Hamady et al. [2] studied experimentally and numerically the heat transfer due to natural convection in an inclined enclosure. Dalal and Das [3] studied the laminar natural convection under variable temperature conditions inside an enclosure with one inclined wavy wall. It was determined that the inclination angle affected the heat transfer rate. The numerical study of natural convection in enclosures with inclined, flat and dome-shaped ceilings was performed by Morsi and Das [4], who determined that the model with the dome-shaped ceiling has the highest heat transfer rate compared to other studied models. Vasseur et al. [5] studied analytically and numerically the heat transfer due to natural convection in a composite inclined enclosure. The Rayleigh number was predicted at the start of convection in a bottom-heated system. These results were compared to the numerical results. Horibe et al. [6] experimentally

---

* Corresponding author.
E-mail address: elanguri@tntech.edu (E.M. Languri).

http://dx.doi.org/10.1016/j.seta.2017.09.009
Received 12 July 2017; Received in revised form 13 September 2017; Accepted 29 September 2017

Please cite this article as: Vinayak Prabhu, V., Sustainable Energy Technologies and Assessments (2017), http://dx.doi.org/10.1016/j.seta.2017.09.009

Nomenclature

Parameter	Description, Unit
A	area, m^2
c_p	specific heat capacity, J/(kg·K)
g	acceleration coefficient of gravity, m/s^2
h	heat transfer coefficient, $W/(m^2 \cdot K)$
HR	humidity ratio
k	thermal conductivity, W/(m·K)
Nu	Nusselt number
p	pressure, N/m^2
q	heat transfer rate, W
q''	heat flux, W/m^2
$\mathbf{u}$	velocity vector (u, v), m/s
t	time, s
T	temperature, °C
x	coordinate, m
y	coordinate, m

Operators

∇	differential operator
∂	partial derivative operator
Δ	increment

Greek letters

β	volume coefficient of expansion of air due to temperature difference, $1/K$
μ	viscosity, Pa·s
ρ	density, kg/m^3

Subscripts

ambient	ambient
door	door
ECU	environmental control unit
in	interior
L	latent
out	outside
S	sensible
0	reference value
∞	ambient

studied the natural convection due to horizontal heated plates in an enclosure. They stated that the heat transfer between the heated plate and the cooled top surface was increased due to the vortex motion between the two plates. They also observed a significant increase in the vortex motion as the heated plate was moved closer to the cooled top surface. Tong and Gerner [7] studied natural convection in rectangular enclosures with partitions filled with air. They found that inserting a partition halfway between the two walls of the enclosure could cause the most reduction in heat transfer. Turkoglu and Yucel [8] studied natural convection in enclosures with several conducting partitions. They observed that as the partitions increase, the mean Nusselt number increases. Also, it was found that the mean Nusselt number does not change with the considered aspect ratios. In the study conducted by Bae et al. [9], natural convection flow in a multiple-partitioned rectangular enclosure was analyzed. The results of the numerical analysis were validated with the analytical model. It was found that as the Rayleigh number increases, the Nusselt number increases but the increase in the partitions decreases the Nusselt number. Hu et al. [10] analytically investigated the role of solid obstacles on laminar natural convection in enclosures to find an arrangement that would increase heat transfer. Zemani et al. [11] numerically studied natural convection in an air-filled cubical enclosure with a hot curved surface and partial barriers. It was found that the heat transfer reduces due to the partitions for a fixed Rayleigh number. It was also found that the heat transfer reduces as the partition length increases. The heat transfer and natural convection flow around a triangular cylinder kept in a square enclosure is analyzed by Sahu and Singh [12]. The fluid flow increases as the dimensions of the enclosure increase. At the top of the enclosure, the heat transfer rate was found to be high.

Natural convection plays an important role on the air conditioning needs of typical flexible shelters. Natural convection in irregular enclosures is also studied by researchers. Coulter and Guceri [13] studied the natural convection in enclosures with irregular shaped walls. The rate of heat transfer obtained from the study was the greatest over the geometric contractions. Triveni and Panua [14] numerically studied the natural convection in a triangular space with a hot wall and the C-shaped curve. It was reported that the flow of fluid and heat transfer were affected by the position of the cold wall, and also the Nusselt number increased when the curved wall was used instead of the flat wall. Kamiyo et al. [15] carried out another study concerning the triangular enclosures. The study concluded that the heat transfer rate reduces as the pitch angle increases irrespective of the Rayleigh number. Hussain [16] performed a similar study using a tilted square enclosure with a triangular-shaped top wall [16].

Various flow models have been used historically to study the natural convection in enclosures. Altac and Ugurlubilek [17] numerically assessed the various turbulent models for heat transfer due to transient turbulent natural convection in rectangular enclosures. Wu and Lei [18] analyzed turbulent natural convection coupled with radiation in a cavity heated unevenly using a numerical method. The effect of 2D and 3D geometry and different turbulent models was also analyzed. It was found that the 2D and 3D models can capture the velocity and temperature profiles in the boundary layer, but the 2D model does not capture the interior stratification. The RANS (Reynolds-Averaged Navier Stokes equations) turbulent models performed well in determining flow structure and calculating unsteady quantities.

Researchers have been working several years to improve the energy efficiency of shelters. Riemer's research [19] discusses the methods to design thermally efficient, transportable, collectively protectable shelters. Riemer [19] provided some conceptual ideas for improving the shelter configuration. In research performed by Martinez-Martin and Thrall [20], the optimization of minimum weight and maximum energy efficiency was analyzed by using honeycomb core sheets. In another study conducted by Salvalai et al. [21], the thermal efficiency of a multilayer insulator was analyzed and simulated through emergency structure applications. The thermal properties of the multilayer insulator were calculated and compared to available literature. The

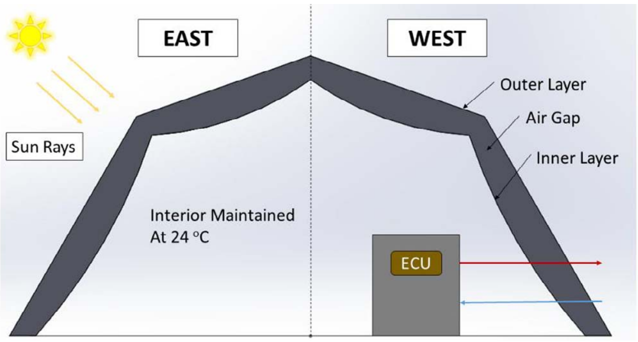

Fig. 1. Schematic diagram of shelter setup.