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Numerical Simulations and energy analysis of heat pumps usage in pre manufactured homes

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ABSTRACT

Energy conservation, economy, and environmental comfort are among the major functional considerations in buildings. There are many important elements that contribute to heating and cooling loads reduction in buildings such as the proper size and orientation of the solar apertures, amount of thermal insulation, and the amount and placement of the thermal storage mass within the living space. Manufactured homes are one of the most common homes for low income families in the United States. These houses are built in factories and shipped to the site. Most of these houses are heated by electric resistance furnaces which basically provide a little less than 1 kWh of heat of each 1 kWh of electricity consumed. Although the initial cost of this system is low compared with other heating systems such as heat pumps, the running cost of the electric resistant heater is much higher than heat pumps. This paper presents a simulation model developed to estimate energy savings and the comfort level when using heat pumps as heating systems. The model is developed for manufactured homes (mobile homes) and is validated with field measurements, actual electrical consumption, and annual building data for different homes at eastern North Carolina, USA. Measurements include field monitoring of indoor temperature, outdoor temperature, mean radiant temperature, heating system supply air temperature, and heating system running cycle of mobile homes. Results from the simulation model developed using the U.S. Department of Energy's code EnergyPlus© provide another

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support to the cost savings of heat pumps. The model showed that the annual electric consumption of the heat pump was 47% of the same home when an electric resistance was used as a heating source. Moreover, peak electric consumption was only 6.3 KW.h when using heat pumps compared to 14 KW.h when using electric resistance as a source of heating. In addition, results from the simulation model show that heat pumps help maintain a comfortable indoor temperature and the surface temperature of the interior is approximately 12% higher with heat pumps than that with electric resistance.

1. INTRODUCTION

Optimizing the air-conditioning and electrical lighting operation also has the potential to significantly lower energy consumption. Many studies have been conducted to predict the contribution of each of these elements to energy conservation(Poel 2007; Yildiz 2009; Dixon 2010; Zhai 2011). Previous studies have highlighted general rules and design guidelines, which are intended to improve building energy performance in standard building designs. Field experiments and computer simulations were also used to determine and to predict building performance, define preferred building design solutions, and suggest new building design alternatives (Hong 2000; Strand 2005; Dixon 2010; Elsawaf 2012; Elsawaf 2013).

Traditionally, manufactured homes (formally referred to as mobile homes) are one of the most common homes for low income families in the United States. These houses are built in factories and shipped to the site. The sizes of these house range between 100 and 220 m^2. Most of these houses are heated by electric resistance furnaces which basically provide a little less than 1 kWh of heat of each 1 kWh of electricity consumed. Although the initial cost of this system is low compared with other heating systems such as heat pumps, the running cost of the electric resistant heater is much higher than heat pumps.

Now a day, heat pumps for space heating and air conditioning have been used extensively in many countries. Heat pumps were introduced to the home heating market in the 1950's, evolving originally from central air conditioners which featured a reversing valve and a few other factory components allowing the heat pumps to provide heat under mild weather conditions. Early models were plagued with reliability problems related to failed reversing valves, improperly operating compressors or frost build up on the evaporators. Performance under colder conditions was often poor due to reduced heating capacity at low outdoor temperatures. Comfort was another complaint with early systems due to "cold blow" where the air temperature delivered by the heat pump (about 38 - 41^{o}C) was much lower than that delivered by natural gas furnace systems (about 52 - 54^{o}C). Modern heat pump systems are much more reliable and have become exceedingly common in moderate climates. By far the most common types are air-to-air heat pumps which use outdoor air as the heat exchange medium. The problems with inadequate capacity and "cold blow" have been reduced by the addition of auxiliary resistance strip heat systems with a two-stage thermostat. As the indoor temperature drops, the first stage activates the heat pump; the second stage below it activates auxiliary strip heat. Under this regime, both the heat pump and the resistance heat operate together until the thermostat is satisfied.

The efficiency of the heat pump has two measures: (1) Heating System Performance Factor (HSPF), which is the ability of heat pump to extract heat from the heat source, usually the outside air, and to expel it into the home (2) Seasonal Energy Efficiency Ratio (SEER) which indicates its ability to extract heat from the home and to expel it into the outside air. Usually a residential heat pump takes low-temperature heat from an outdoor medium (such as air, ground, groundwater or surface water) and mechanically concentrates it to produce high temperature heat suitable for heating the interior of homes. Because most of the heat is moved (pumped) from the outdoor source to the indoor source, the amount of electricity required to deliver it is theoretically much less than using electric resistance heat directly. In the past, utility demand-side management programs have strongly leaned on heat pumps to reduce winter peak coincident demands.

The goal of this paper is to develop a simulation model to determine the energy saving at manufactured homes when using heat pumps for heating. The model is validated using field measurements obtained from manufactured homes during the winter season.

2. BACKGROUND OF THE STUDY

Approximately one-third of the new homes sited annually in North Carolina are manufactured homes. This percentage is considerably higher in rural areas of the state. Since manufactured homes are built in a factory and then delivered to permanent home sites, US federal regulations by the Department of Housing and Urban Development (HUD code) require the installation of heating systems while the home is being constructed. Almost all manufacturers install forced air electric furnaces in the homes that they build. Rationale for this installation choice is based on lower initial cost and simplified installation. The duct system and associated connections is designed and installed to accept either an air conditioning and/or a heat pump unit without undue modifications or expense to the home owner. Both air conditioning units and heat pumps are installed after the home is permanently sited. As previously cited, forced air electric-resistance furnaces have a lower first-cost; however, they are typically 2 to 3 times more expensive to operate than a heat pump. The home owner’s additional operating expense could be as great as $200 to $300 per winter month. Many customers choose manufactured homes because they offer an inexpensive housing option for their families. The benefits of a lower monthly payment are often negated by the additional monthly operating expense of an electric-resistance furnace. In some instances, the monthly winter utility payment may actually be higher than the monthly mortgage payment.

Although heat pumps have higher initial cost that most other heating systems, their energy consumption (running cost) is generally lower in moderate climates such as North Carolina. Despite their relatively higher initial costs, the popularity of heating pumps is increasing. For example, in North Carolina, heat pumps are highly competitive because they can meet the entire cooling and heating needs of residential buildings. Previous research such as Gustafsson and Bojic (Gustafsson 1997) recommended that the optimal heating-system retrofits in residential buildings is using heat pumps alone as heating systems. The present work focuses on determining the efficacy of upgrading the heating system and using heat pumps as the main source of heating in eastern North Carolina pre manufacturing residential homes.

3. FIELD MEASUREMENTS

Temperature measurements were conducted at different houses during three heating seasons. It is known that if the heating is not continuous and is turned off for a period of time, the house cools and some energy will be required to reheat the house when it turned on. In all of the measured houses the householders do operate their heating systems continuously. Portable computers with LabVIEW software, data acquisition cards, and four thermocouples were installed in each house for about two-weeks. As shown in Fig. 1, the four thermocouples were connected to the computer through the data acquisition card and extended to four different locations in each house to measure the following: outdoor temperature, supply air temperature, indoor room temperature, indoor wall temperature. The four temperatures were measured and recorded every 10 seconds (Fig. 2).

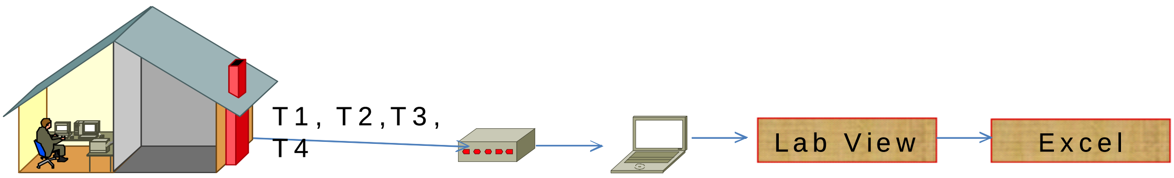

Fig.1. Measured data recording process

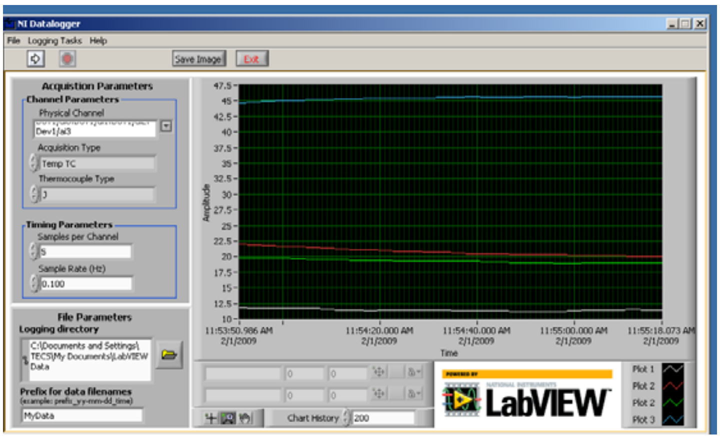

Fig. 2 Screen shot of the data acquisition and LabVIEW output window

The data was exported from the LabVIEW software to Microsoft Excel for analysis. The duty cycle of the compressor of the heat pump was monitored using the supply air temperature data which provided detailed information about the energy consumption used to heat the house. Figure 3 shows an example of the recorded data represented graphically in Excel. The figure shows when the heat pump is operating in direct correlation to the outside temperature. As the outside temperature drops, it is easy to see that the indoor duct temperature is increasing showing that the heat pump is on.

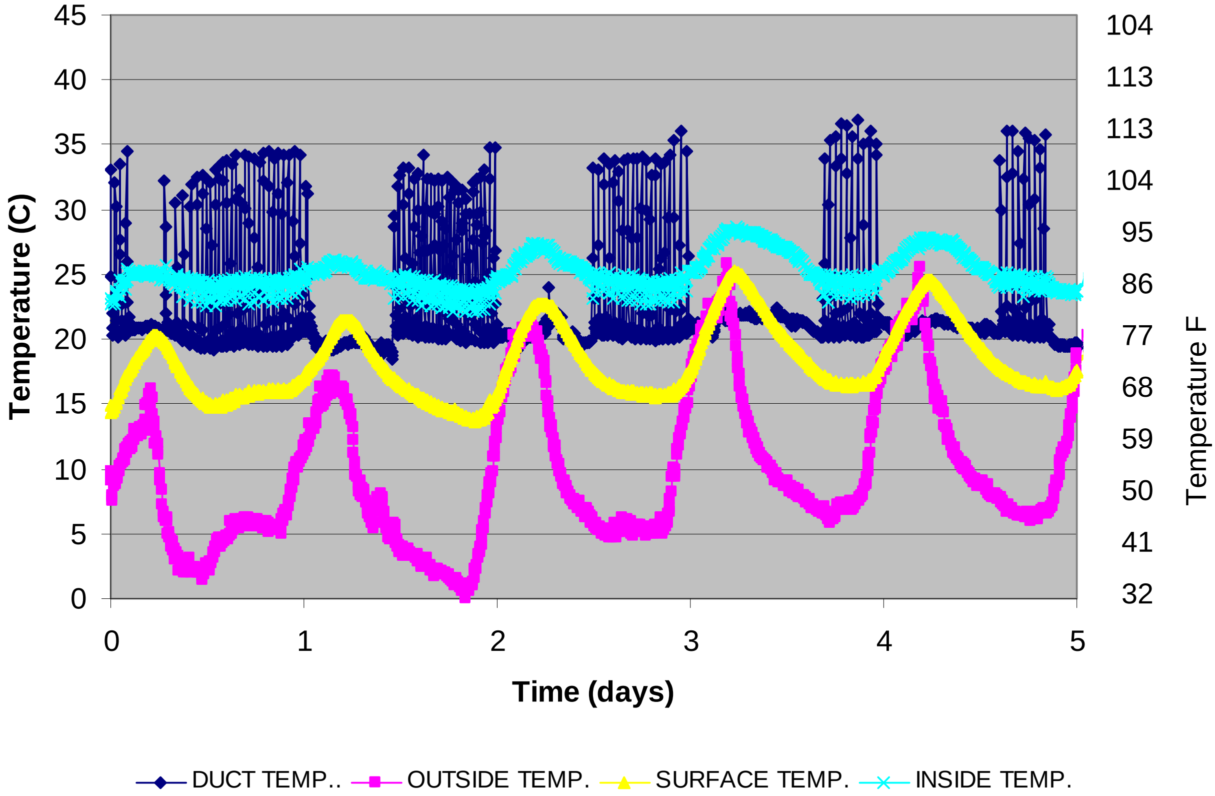

Fig.3 Temperature distribution from one of the manufactured homes.

4. NUMERICAL SIMULATION MODEL

A simulation model was created to predict the annual saving of replacing the electric resistance with a heat pump in mobile homes. The simulation model was also used to verify the indoor comfort level when heat pump is used for heating. A simulation model for a typical mobile home was created using Energy Plus (Crawley 2001; Energy 2011) This software developed by the United States Department of Energy (DOE) and combines the major factors of other energy analysis tools that were developed by DOE. Energy Plus was selected in simulating a typical house for the following reasons(Energy 2011); (i) DOE published the engineering reference for the software which provides insight of the mathematical formulas that is used in the simulation calculations. This features helps in better understanding the effect of the different building components on the overall energy consumption. (ii) The software accounts for convection and radiation in the calculations. This feature is critical to our analysis since it accurately accounts for thermal comfort.(iii) The software has tested examples for modeling heat pumps.(iv) Energy Plus had a good reputation and it was by the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) to validate the new ASHRAE Energy Standard for Buildings Except Low-Rise Residential Buildings 90.1(ANSI/ASHRAE-90.1-2010 2010).

The model is created to predict the annual savings generated by replacing the factory installed electric resistance heater with a heat pump in manufactured homes. The filed survey and comments from participants highlighted some concerns that heat pumps do not provide indoor thermal comfort conditions. Therefore, the simulation model is also used to verify the indoor comfort level when heat pump is used for heating. The model is created for a typical manufactured home that consists of 120 m^2 (Fig. 4). Walls must be built with kiln dried, #2-grade or better lumber; must be built with at least a 4-inch outer wall and maintain insulation values or R-11 for those of us in zone 2; all electrical wiring is protected from puncture by steel strapping. An actual yearly weather data was used in the present simulation. One of the measured homes

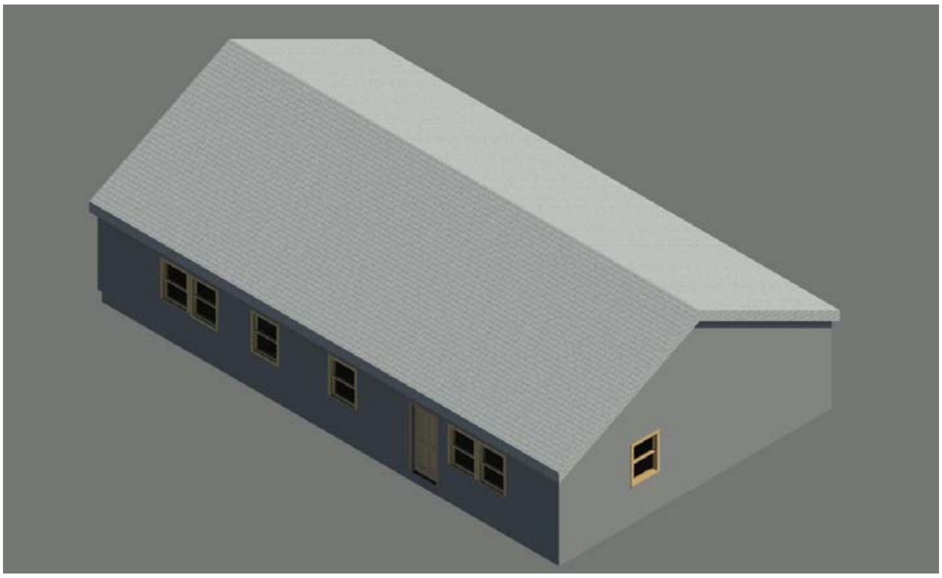

Fig.4 Perspective view of the simulated pre manufactured house

was used in the simulation input. The goal of the simulation to compare the electric resistance and the heat pump heating systems for the same house rather than finding the exact power consumption of the house in a great accuracy. An extensive simulation model calibration would require installing a weather station, conducting a blower door test and duct blasting tests to calculate infiltration rates, as well as installing a sub meter for the HVAC systems at the tested house.

5. SIMULATION RESULTS

To calibrate and validate the simulation model, a set of 7 consecutive days of similar outside weather condition and inside comfort level were selected from the field data to represent the house performance; outside air temperature readings from the data logger were used in the model calibration. Since most pre manufactured houses are located in an open rural area, data from the nearest weather station for the solar radiation; wind velocity, relative humidity, and precipitation were used in calibrating the simulation model. The measured duct's air temperature along with outside air temperature were also used to determine the duty cycle and to calculate the actual HSPF and the power consumption of the HVAC system. This data was also used in the model calibration. Since many of manufactured homes are Energy Star Rated, maximum infiltration rates allowed by Energy Star rating were used for the infiltration rates. The simulation software weather data file was modified to match the above set of weather conditions. The calculated power consumption of the heating system was matched with the simulation results. In addition, the actual readings of the inside air temperature were matched to the inside air temperature which was obtained by the house simulation and is presented in Fig. 5. The correlation coefficient between the measured indoor temperature and the simulated indoor temperature was 0.93.

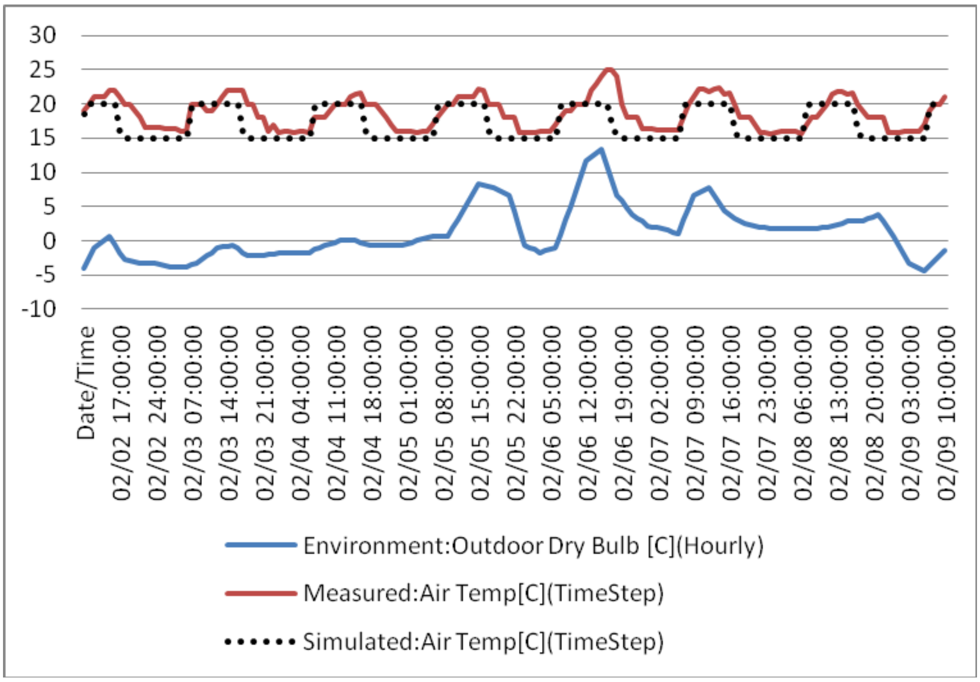

Fig. 5 A conmparison between the measured indoor air temperature and the indoor simulated air temperature

To predict the annual electric saving of replacing the heat resistance with a heat pump, the mobile home was first simulated with an electric heater as a sole heating source. Second, the house was simulated with the heat pump as the main heating source, and electric resistance was used as an auxiliary heater.
The simulation results of the calibrated model showed that when using a heat pump as a main heating source, the mobile home maintained an indoor air temperature above 21º C of 97% during the heating season (Fig. 6) compared to 96% when electric resistance was used as a main heating source as shown in Fig. 7.These results show that heat pump under continuous operation is as effective as conventional electric heat resistance in achieving comfort temperature in mobile homes.

When comparing the annual simulated electric consumption of the HVAC heating system in the mobile home results show that the annual HVAC system electric consumption of the mobile home when the heat pump was used as a main heating source was 5986 kWh compared to12646 kWh when the electric resistance was used as an alternative heating source Thus, the annual electric consumption of the heat pump was 47% of the same home when an electric resistance was used as a heating source. The simulation results of the hourly electric consumption are presented in Fig. 8. This figure shows that the peak electric consumption of the electricity when using electric resistance as a main source for heating has reached 14kW.h, compared to a peak electric demand of 6.3 kW.h when using the heat pump. Although utility companies in North Carolina do not charge residential customers for peak load demand, reducing peak demand generally reduces the overall electricity cost.

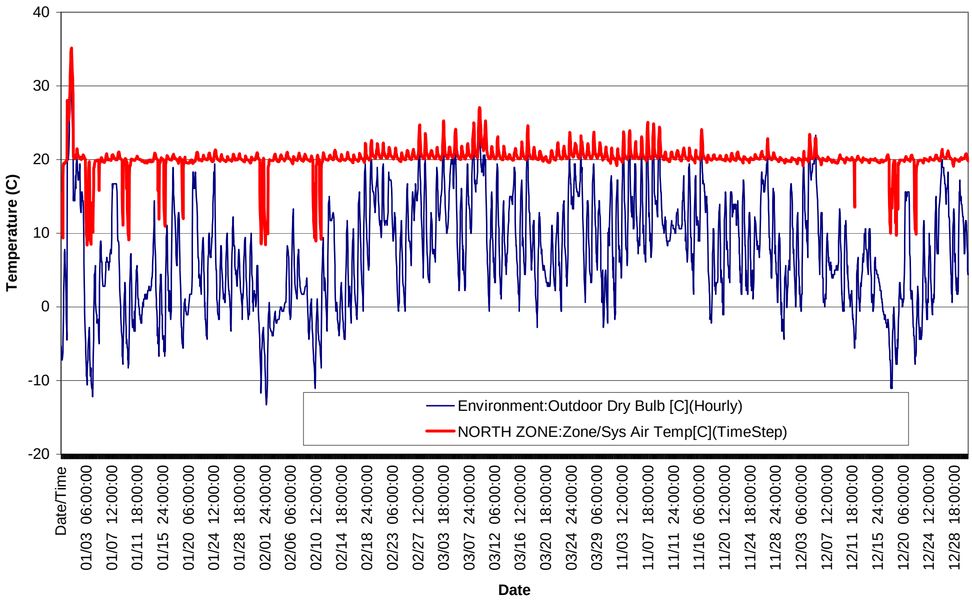

Fig.6 The simulated indoor hourly air temperature in a mobile home with a heat pump as the main heating source

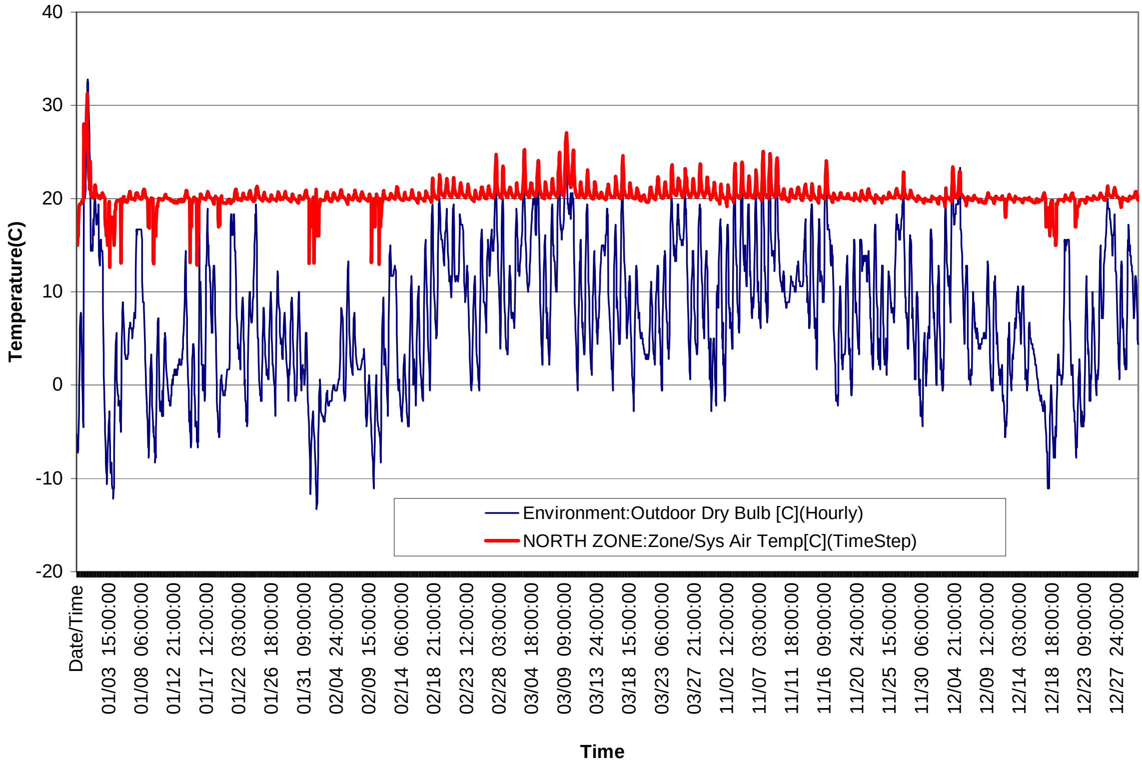

Fig.7 The simulated indoor hourly air temperature in a mobile home with an electric resistance as the main heating source

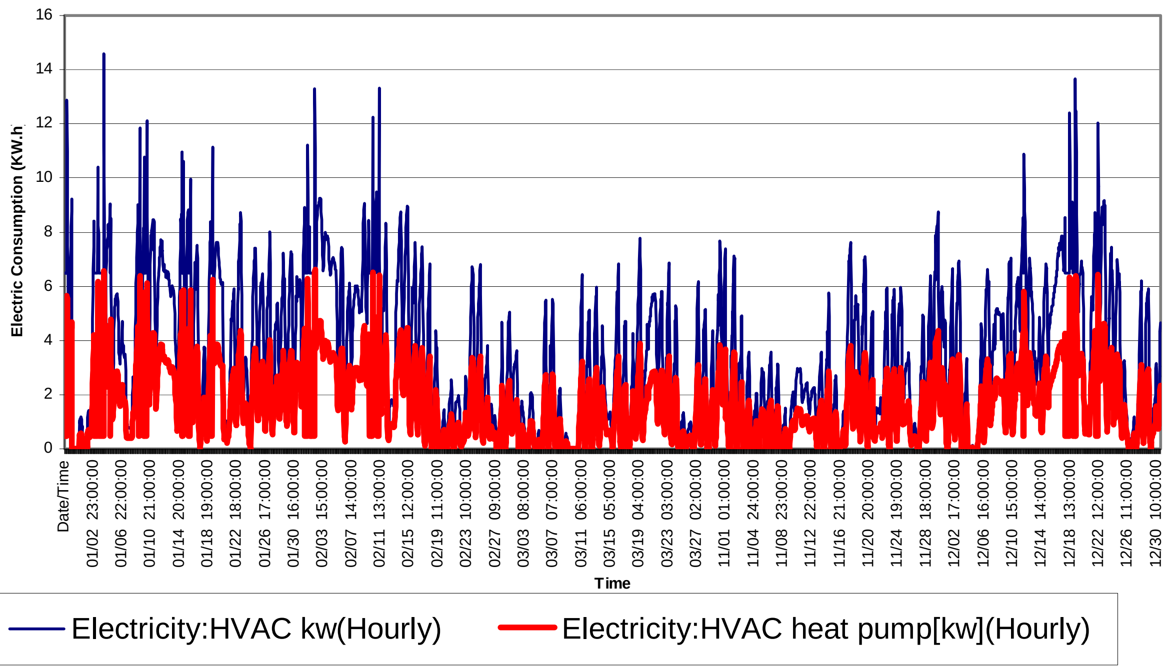

Fig.8 Comparison of electrical consumption

Many utility companies including those of North Carolina have their own incentive plans to encourage customers to shift from electric resistance heating system to the heat pump system. The simulation results showed that the heat pump runs approximately 28% of the entire heating season (November to March) while the electric resistance runs for approximately 18% of the entire heating season. The simulation results showed that although both systems has maintained comfortable indoor temperatures, the surface temperature of the interior was approximately 12% higher when using the heat pump. Since the thermostat set point for both systems were maintained at the lower end of the comfort level (21º C), higher surface temperature will insure a higher thermal comfort satisfaction. An in-depth analysis of comfort satisfaction was beyond the scope of this research.

7. CONCLUSIONS

In this study, numerical simulations are performed and presented for pre manufactured homes. the numerical model was calibrated using field measurements. Measurements include field monitoring of indoor temperature, outdoor temperature, mean radiant temperature, heating system supply air temperature, and heating system running cycle of mobile homes. Numerical results from the simulation model are developed using the U.S. Department of Energy's code EnergyPlus© . The model showed that the annual electric consumption of the heat pump was 47% of the same home when an electric resistance was used as a heating source. Moreover, peak electric consumption was only 6.3 KW.h when using heat pumps compared to 14 KW.h when using electric resistance as a source of heating. In addition, results from the simulation model show that heat pumps help maintain a comfortable indoor temperature and the surface temperature of the interior is approximately 12% higher with heat pumps than that with electric resistance.

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