Energy and Air Infiltration Monitoring of Manufactured Homes in Cold Dry Climates

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ABSTRACT

Single- and double-section manufactured homes were instrumented in 2001-2003 to measure continuous energy usage and air infiltration with respect to the environmental conditions of a windy cold dry climate. The test site near Arlington, Wyoming, USA is ideal for testing the energy (and structural) performance of manufactured housing due to the naturally occurring high winds (in excess of 35 m/s annually) and temperature extremes (+35º to –35ºC). Tests included tracer gas monitoring, pressurized leakage tests, and infrared (IR) video scans. Extensive arrays of instrumentation for calculating thermal efficiency of the homes were designed and installed. Thermocouple arrays were placed to measure vertical temperature profiles in various locations in the homes. At each location, the air temperature in the crawl space, belly pan, near-floor, room center, ceiling, and in the attic were monitored. Additional temperature measurements were located at the furnace thermostat and return air plenum, heater vents, combustion air inlet, and flue gas exit. Electrical power consumption and propane flow complete the measurements required for monitoring thermal efficiency. Measurements indicate that a transpired air solar heater provides up to 40% of the energy required to heat the double-section home. The tracer gas concentration decay measurement system provided useful data showing a strong correlation of the air infiltration rate with ambient wind speed. These data were used in conjunction with EnergyPlus software to simulate the thermal performance of the double-section home.

KEYWORDS

Manufactured housing, air infiltration, energy efficiency, EnergyPlus, solar wall, wind effects.

INTRODUCTION

The Idaho National Engineering and Environmental Laboratory (INEEL) is investigating whole building integration of energy efficiency and air infiltration in residential buildings; primarily manufactured housing installed in the cold, dry, and windy climates of the western US. New technologies to detect infiltration, simulation tools, and products that improve the building envelope are being developed/investigated and tested. Manufactured homes have been instrumented to measure continuous energy usage and air infiltration with respect to environmental conditions. Other tests included tracer gas monitoring, pressurized leakage tests, and infrared video scans. These data are used to evaluate the energy utilization, identify design and material improvements, support design and inspection guidelines, and provide data sets useful for energy analysis and air infiltration computer code verification. Data has also been collected to measure the effectiveness of a passive solar wall designed for manufactured housing. This paper describes the experiments conducted and results obtained for data gathered during March 2003 on a double-section manufactured home as well as analytical comparisons with measured data.

TEST DESCRIPTION

This paper describes results of tests on a Kit Manufacturing Co. 8.1m x 18.3m (26ft 8 in x 60ft); 3 bedroom and 2 bath double-section home (Kit Manufacturing, 2002; Richins et. al. 2001, Richins et. al. 2003). The home is representative of many homes currently produced and is structurally complete with ducting, insulation, plumbing, electrical system, roofing, siding, interior walls, etc. but without interior trim and most appliances. The home was installed with tiedowns and jack stands and then completely skirted with an uninsulated vinyl product. Testing was conducted at a field site on a plateau near Arlington, WY, USA (80 km west of Laramie, WY). This test site (Fig. 1) is ideal for testing air infiltration and energy performance of housing structures due to the naturally occurring high winds (in excess of 35 m/s annually) and temperature extremes (+35º to –35ºC). The home was uninhabited and a constant inside temperature of approximately 10ºC was maintained.

A SolarWall© heater (Fig. 2, Conserval Inc. 2003) was installed near the home and ducted into the kitchen/dining area. The SolarWall heater is an unglazed perforated 2.0m x 2.4m (80 in x 96 in) collector. Outside air drawn by a fan enters the absorber (a perforated metal sheet with the general appearance of conventional metal siding), is heated by solar energy as it progresses up the absorber, discharges into a plenum, and then is exhausted through insulated ducting. The SolarWall was installed with SE exposure, tilted up at 53 degrees from horizontal, and sheltered from the wind (prevailing SW direction) by the home as much as possible (Fig. 2). A control system, with set point of 21ºC, turned on a fan (measured 2.1 m^3/min or 73 CFM air flow) to blow warm air into the home if the interior is below the set point and the air in the solar wall is above the set point. The SolarWall was in the building shadow by approximately 3pm (USA Mountain Standard Time) in March 2003.

An automated air infiltration sensor based on CO_2 concentration decay rates was developed and installed in the home. Once per day (at 12:30am USA Mountain Standard Time), CO_2 was injected for approximately 10 minutes to bring the indoor CO_2 concentration up to 2000 ppm. The injection was stopped, fans were used to provide adequate mixing, and the decay in CO_2 concentration in the building was measured.

Thermocouples were installed to measure vertical temperature profiles in three locations in the home: the south bedroom, the central room, and the north bedroom. At each location, temperatures were measured in the crawl space, belly pan, air near the floor, center of the room, near the ceiling, and in the attic. Additional temperature measurements were located near the furnace thermostat, at the return air plenum, at the heater vent closest to the furnace, at the heater vent farthest from the furnace, at the combustion air inlet, and at the flue gas exit. Total electrical power consumption and propane flow to the furnace complete the measurements required for monitoring thermal efficiency. Three anemometers and air temperature and relative humidity measurement systems were installed on a weather tower upwind of the manufactured home to gather local weather data. Solar insolation was measured so the effects of incident solar radiation could be accurately accounted in the energy balance. Thermocouples were also used to monitor the SolarWall performance. Data was recorded locally on a personal computer using National Instruments and IOTech hardware and LabVIEW software (National Instruments Inc. 2003, IOTech Inc. 2001, LabVIEW 2002).

DATA PROCESSING AND INTERPRETATION

Air Infiltration Tests

Air infiltration was calculated with the two-point decay technique of Sherman (1998) using the first hour of CO_2 concentration decay data (Fig. 3) and an interior house volume of 368.6 m^3. Figure 4 shows an example of estimating air changes per hour using the two-point decay method with increasing time periods. Note that the air change rate is relatively constant with time periods from 1 to 2 hours after initial injection and mixing of the $CO_{2.}$

Figure 5 shows the infiltration rate results of 16 tests as a function of wind speed at the elevation of the eaves (averaged over the first CO_2 decay hour). A linear regression fit to the data is also shown. Wind direction was relatively constant (bearing ranging from about 245 – 280 degrees True North, longitudinal axis of home has bearing of 11.3 degrees True North). While there is a strong correlation of the infiltration rate with ambient wind speed, no meaningful correlation between outside air temperature and air infiltration was apparent.

SolarWall Tests

The performance of the SolarWall system is summarized in Figs. 6 – 7. Solar insolation was measured vertically using a Licor Model LI200X Pyranometer on the roofline of the manufactured home. The temperature within the SolarWall increases as the sun starts shining on the wall and continues to increase until the SolarWall fan set point (21ºC) is reached. The fan draws air from the SolarWall decreasing the temperature within the SolarWall as cool air is drawn in through perforations in the collector. The warm air in the SolarWall passes through a register into the manufactured home increasing the interior temperature of the home. The home interior temperature is measured at the register where the SolarWall heated air enters the kitchen. On March 14, 2003, the SolarWall fan comes on at 07:25 and remains on until 17:05 (USA MST). Note that the damper used in the SolarWall ducting was rather inefficient, not sealing completely, and has been improved in subsequent models.

The SolarWall added energy to the home when the SolarWall fan was operating (air above set point of 21ºC). The energy added to the house by the SolarWall was calculated by the mass flow of the air (when the SolarWall fan was on) times the difference between the enthalpy of the warm air flowing into the building and the outside (ambient) air. Electricity and propane are the only additional energy sources used in the calculation of the energy provided by the Solar Wall. The heat energy contribution due to the SolarWall (during daylight hours) is shown in Figure 7. When the outside air temperature was above about –5ºC and the SolarWall was exposed to sunlight, the SolarWall system provided a significant percentage of the energy required to heat the home - up to 40% when the outside air temperature was about +10ºC.

Since the set point for the SolarWall fan was 21ºC, heated air (warmer than outside air but cooler than the set point) within the SolarWall was often not used. Discharging air cooler than this set point into the living space would be uncomfortable for most occupants. An efficient SolarWall installation in a new manufactured home might duct warm air directly into the air plenum of the furnace for pre-heating and to meet ventilation requirements as well as discharge heated air into the living space when the temperature set point was exceeded. A control system would be required to more efficiently handle the air flow either directly into the home living space or to the furnace plenum.

Energy Usage and EnergyPlus Modeling

The US Dept. of Energy (DOE) energy simulation software package EnergyPlus (EnergyPlus 2002) was used to model the double-section manufactured home and calculate interior temperatures. The EnergyPlus model was developed to characterize the thermal behavior of the building and actual building dimensions, materials, window data (orientation, dimensions, E-value), and site orientation were used for the basic model. The model included the geometry, materials (including insulation) and thickness for the walls, roof, and floor. Site-specific weather data (dry bulb temperature, calculated dew point temperature, relative humidity, atmospheric pressure, wind speed, wind direction, and solar radiation) were assembled in 10 minute increments to develop “weather files” for required EnergyPlus input.

Results from the EnergyPlus simulation were compared with the home measured interior temperature (Fig. 8) to verify the model. While the comparison between the calculated and measured temperatures shown in Figure 8 is reasonably good, numerous issues had to be addressed during the course of the model development and conduct of calculations. For example, a furnace system efficiency of 60% (including ducts, crossovers, registers) was used for the calculation shown in Figure 8 even though the furnace nameplate states an efficiency of 80%, since such resulted in a better comparison to the measured data. We believe this could be related to true furnace efficiency as well as belly pan leakage and are currently investigating such issues. In spite of these issues, we are confident that the EnergyPlus model can now be used to conduct what-if scenarios to evaluate the energy benefits of better insulation, a more efficient furnace system, improved windows, etc.

CONCLUSIONS

An automated air infiltration sensor based on CO_2 concentration decay rates was developed and shown to be an effective method to measure air infiltration in windy climates. Test results indicate that adequate mixing within the building is critical to achieve high quality and consistent results. Air infiltration tests using CO_2 decay rates show a near linear correlation between air changes per hour and wind speed.

The energy benefits of supplementing space heating with a SolarWall system was investigated. When the outside air temperature was above about –5ºC and the SolarWall collector was exposed to sunlight, the SolarWall system provided a significant percentage of the energy required to heat the home - up to 40% when the outside air temperature was about +10ºC. An efficient SolarWall installation in a new manufactured home might also consider ducting warm air directly into the air plenum of the furnace for pre-heating and to meet ventilation requirements in order to take advantage of air that is warm but not warm enough to comfortably discharge into the living space. A control system would be required to more efficiently handle the air flow either directly into the home or to the furnace plenum.

An EnergyPlus model of a double-section manufactured home was developed. Calculated interior home temperatures compare well with measured values. While some modeling issues exist, the model can now be used to simulate the energy benefits of better insulation, a more efficient furnace system, improved windows, etc.

ACKNOWLEDGMENTS

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DISCLAIMER

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Figure 1. Double-section test home installation near Arlington, WY, Fall 2002.

Figure 2. SolarWall system on manufactured home, Arlington, WY, Winter 2003.

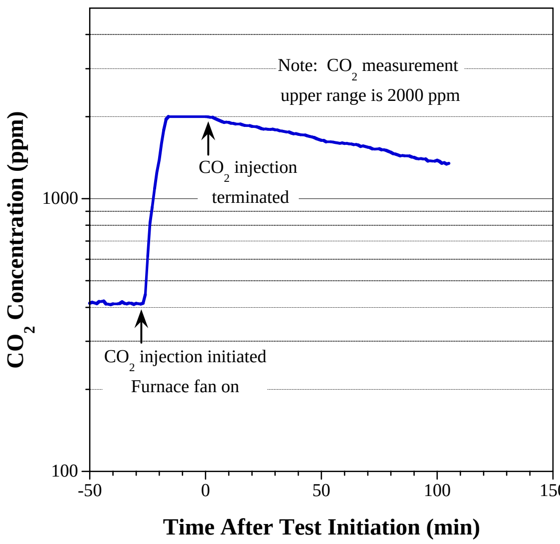

Figure 3. CO_2 concentration as a function of time after the experiment started.

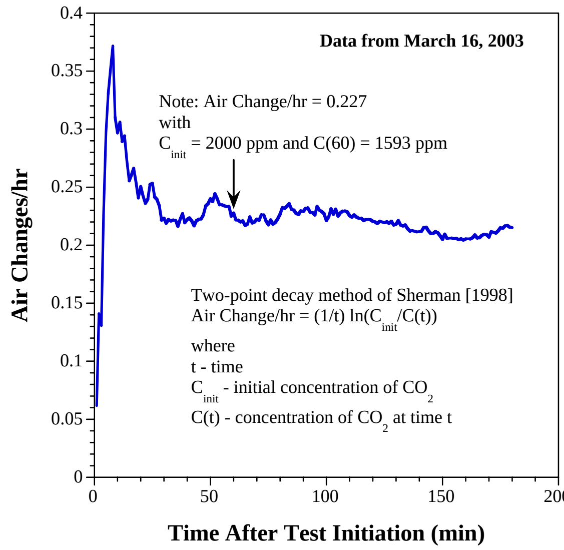

Figure 4. Air changes per hour using the two-point decay method of Sherman [1998] with increasing time.

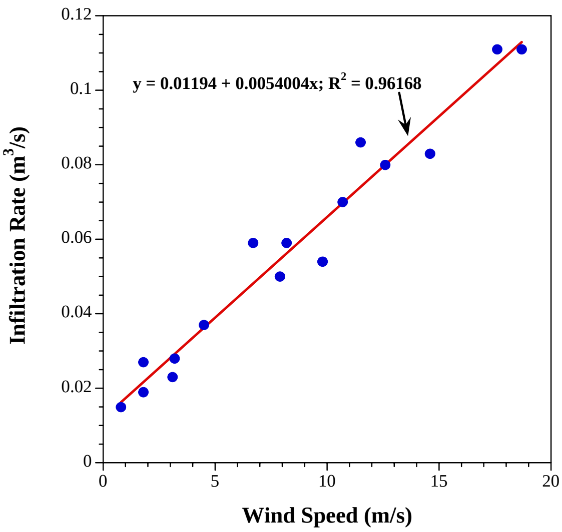

Figure 5. Infiltration rate data and linear regression as a function of wind speed for double-section manufactured home.

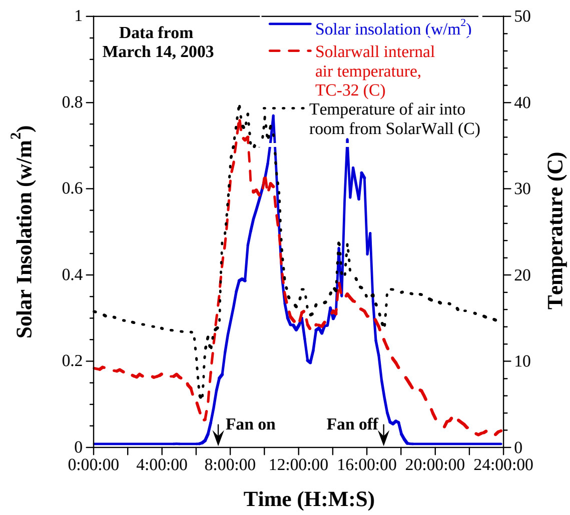

Figure 6. Comparison of SolarWall internal air and exhaust temperatures and solar insolation.

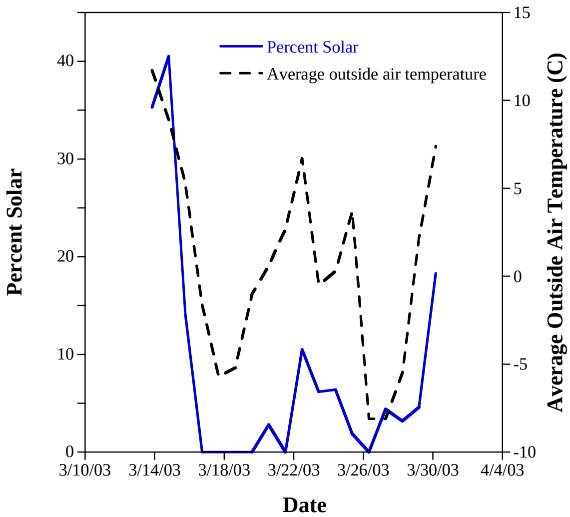

Figure 7. Percent of total energy contributed by the SolarWall and average outside air temperature as a function of date during daylight hours.

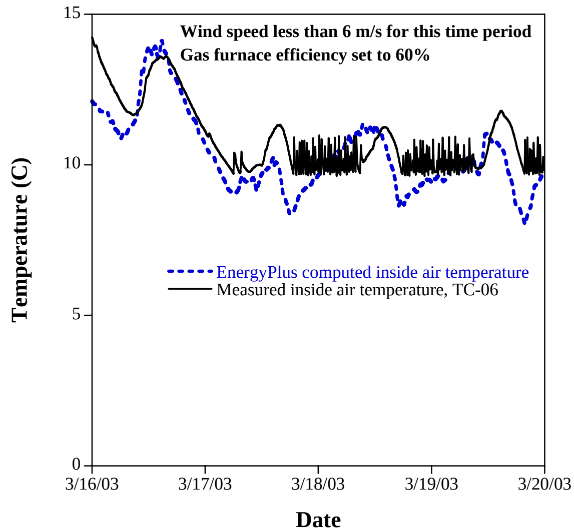

Figure 8. EnergyPlus computed inside air temperature with furnace efficiency of 60% and measured inside air temperature as a function of time.