Transient Thermal Response of an Intermittently Cooled Massive Building

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ABSTRACT

A one-room externally insulated masonry test structure was built inside an environmental chamber at the National Bureau of Standards. This structure was exposed to diurnal sol-air summer temperature cycles, and two energy conservation schemes were investigated. For both schemes, the interior mass of the structure was cooled during the night hours, first by mechanical cooling and second by ventilation with outdoor air. The results indicated that mechanical cooling effectively cooled the interior mass during the night hours such that no additional daytime cooling was needed for even the most extreme summer conditions. The tests further indicated that ventilation with outdoor air effectively cooled the structure to the point where no mechanical cooling was needed for summer conditions representative of many parts of the United States.

The experimental test results compared well with those obtained from an analytical model.

Key Words: Energy conservation; night ventilation; night cooling; thermal mass.

INTRODUCTION

The use of building mass to decrease peak energy demand in an air-conditioned building has been previously investigated. These studies (1) have indicated that the daily energy peak demand is reduced with the use of masonry walls which effectively delay the building heat gains. The intent of this study is to demonstrate that the use of massive buildings, coupled with exterior insulation and system operations designed to fully utilize the structure's thermal storage capability, may result in substantial reductions in, and even the elimination of, summer air-conditioning energy usage for many parts of the United States.

Two schemes were investigated. The first scheme utilized mechanical cooling during the night hours to cool the building mass so that it would remain cool throughout the daytime hours. The benefits of this scheme are twofold. First, for many locations, the mechanical equipment operates more efficiently during the cool night hours. Second, it has been shown that the peak load of a central cooling plant servicing many buildings can be reduced by cooling some of the buildings (serviced by the plant) at night (2).

The second scheme investigated the use of night ventilation to cool the building mass so that no mechanical cooling would be required. This scheme has the potential of greatly reducing air conditioning energy and even eliminating it entirely for many typical climates.

To determine the feasibility of the above schemes, an experimental test structure was built in an environmental chamber at the National Bureau of Standards. Summer diurnal temperature cycles were simulated in the chamber and the dynamic building response was recorded. The measured values were compared with those obtained using an analytical model.

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The following sections will discuss the construction and instrumentation of the test structure, the procedure for carrying out the two test schemes, and the test results, with some discussion of their applicability to various climates.

TEST STRUCTURE

The test structure consisted of a one-room masonry building having five windows and a door with external dimensions of 21 ft. (6.4 m) long by 17 ft. (5.2 m) wide by 15 ft. (4.6 m) high. The walls were constructed with 0.75 in. (19 mm) plaster, 8 in. (203 mm) solid concrete block, 3.5 in. (89 mm) rigid polystyrene insulation, 1 in. (25 mm) air space and 4 in. (101 mm) exterior face brick, comprising a unit weight of 131 lb/ft^2 (644 kg/m^2) and a resistance value of 20 $h{\cdot}ft^2{\cdot}F/Btu$ (3.5 $m^2{\cdot}K/W$).

The roof consisted of 8 in. (203 mm) precast concrete panels, 4 in. (101 mm) rigid polystyrene insulation and 2 in. (51 mm) precast concrete pavers, giving a unit weight of 73 lb/ft^2 (360 kg/m^2) and a resistance of 22 $h{\cdot}ft^2{\cdot}F/Btu$ (3.9 $m^2{\cdot}K/W$). A roof membrane for weather protection was not included on the experimental structure. However, one would be included on such a structure built in the field. Figure 1 shows a photograph in which the wall and roof layers are visible. Figure 2 shows a photograph of the completed test structure.

For the first scheme, night mechanical cooling, a gravity cooling unit was used in the structure to provide the mechanical cooling. This unit consists of a chilled-water finned cooling coil that induces air circulation within the room solely from buoyant forces caused by the vertical temperature gradient, thereby eliminating the need for a circulatory fan.

Thermocouples were mounted throughout the structure to monitor the dynamic temperature response of the building. The locations are shown by circles in Figure 3. Each surface thermocouple shown in the figure is adjacent to an additional sensor (not shown) located in the air at a distance of 1 ft. (304 mm) from the surface-mounted sensor. A vertical column containing four thermocouples was centrally located in the south portion of the room to measure the room temperature stratification. A relative humidity transducer was located on the column 4 ft (1.2 m) above the floor.

A thermopile was installed across the supply and return chilled-water pipes to measure the temperature difference of the water as it passed through the mechanical cooling unit. This temperature difference was integrated over hourly periods and multiplied by the mass flow rate and specific heat of water to determine the heat removed by the valance unit.

All transducers were connected to a data acquisition system located in the control room of the environmental chamber. The data acquisition system printed the output signal of all connected stations at a selected time interval.

TEST PROCEDURE

In the mechanical night cooling test, an area-averaged sol-air diurnal temperature cycle, representing an extreme desert climate, was simulated within the environmental chamber. (It should be pointed out that the use of a sol-air temperature cycle increases the amount of window transmission that would be taking place in the field. This increased window transmission partially makes up for the lack of window solar load for the test in the environmental chamber.) The derived sol-air cycle ranged from 75°F (24°C) during the night hours to 136°F (57.8°C) during the day. The test house was mechanically cooled for a 9-hour period extending from 9 p.m. until 6 a.m., during which time the indoor temperature was held constant at 72°F (22°C).

An internal heat gain for two occupants and appliances was simulated using incandescent lamps. The heat gain was set at 1000 Btu/h (293 W) from 7 p.m. through 12 p.m. and at 500 Btu/h (146 W) from 1 a.m. until 7 a.m. The latent heat from the occupants was not simulated, since the focus of the study was on the sensible heat response of the structure. The purpose of this night mechanical cooling test was to determine the amount of temperature rise that would occur during a 15-hour daytime period during which the test structure was exposed to an extreme outdoor summer cycle.

The night ventilation test utilized a sol-air diurnal temperature cycle more representative of summer temperatures encountered in many parts of the United States. This cycle ranged from 68°F (20°C) during the night to 120°F (48.9°C) during the day. The dew point temperature within the chamber was held constant at 57°F (14°C) for the diurnal cycle. Night ventilation of outdoor air was used to cool the structure. The ventilation was induced by opening the windows and door of the test structure and operating a small ceiling-mounted fan to circulate the air within the test building.

The ventilation rate during this period was measured using sulfur-hexafluoride tracer gas and found to be 14 volume changes per hour with the windows open. The ventilation was started at 9 p.m. when the outdoor air temperature fell below the room air temperature. The ventilation was continued until 7 when the outdoor air temperature rose above the room air temperature.

This test investigated the use of night outside air to cool the interior mass, and also the resulting temperature rise during the daytime period.

For each of the above two tests, the sol-air diurnal temperature cycle was repeated until the test structure attained a steady-periodic condition (i.e., recorded temperatures repeated themselves over a 24-hour interval).

The test results are compared with those predicted using an analytical model. The model was developed to calculate the transient thermal response of a building using the z-transform (3) solution for the heat conduction through opaque surfaces. Further information about the model and the algorithms used may be found in Ref. 4 and 5.

TEST RESULTS

For the mechanical night cooling test, the test structure required 4 weeks to reach a steady-periodic condition. The sol-air cycle and the measured and predicted indoor temperatures are shown in Figure 4. When the thermostat was set at 72°F (22°C) during the night, the indoor temperature rose less than 6°F (3°C) during the 15-hour day period when the mechanical cooling unit was not operated. During the same period, the sol-air temperature rose 71°F (39°C). The measured values closely followed the values predicted by the analytical model.

Figure 5 shows the recorded response for the night ventilation test. The sol-air temperature ranged 52°F (29°C) and the indoor air temperature rose only 5°F (3°C) during the day with no mechanical cooling being provided for the entire 24-hour cycle. The recorded indoor air temperature remained below 79°F (26°C), without any mechanical cooling, even though the sol-air temperature attained 120°F (48.9°C) at the daytime peak.

DISCUSSION

The above results indicated that use of mechanical cooling only during a 9-hour night period to cool interior mass resulted in an adequate indoor temperature during the day period. The observed daytime temperature rise of 6°F (3°C) is acceptable, although during this 15-hour period the relative humidity rose to 80% by the time the mechanical cooling system became operative. The source of moisture was determined to be primarily from the masonry surfaces of the test structure. This condition was attributed to the original water contained in the concrete during its construction. A detailed analysis of this is given in Ref. 6.

The sol-air diurnal temperature cycle used for the 9-hour night cooling test was derived from weather data for a desert climate. It is based upon a daytime high ambient all temperature of 110°F (43.3°C) and nighttime low temperature of 79°F (26°C). This temperature cycle is seen to be hotter than all parts of the United States (see Table 1). It is therefore apparent that night mechanical cooling for such a structure is a viable strategy for all locations of the United States.

For the night ventilation test, the measured indoor air temperature remained below 79°F (26°C) without mechanical cooling. The sol-air temperature cycle used for the night ventilation test was based on an outdoor air temperature that ranged from a daytime high of 93°F (34°C) to a nighttime low of 68°F (20°C). No credit for night sky reradiation was used in the derivation of the sol-air temperature because this would create an unrealistic temperature value for the ventilating air. Many regions of the United States are seen to exhibit similar temperature extremes for their peak summer months (see Table 1). Therefore, it is apparent that night ventilation is a viable cooling strategy for this type of construction in most parts of the United States.

For the night ventilation test, the dew point temperature in the chamber was held constant at 57°F (14°C). The relative humidity in the test structure remained below 57% during the daytime period when the test structure was not ventilated due to the relatively low moisture content of the night ventilating air. Table 1 lists the relative humidity at a single time of the day. Many cities, shown in Table 1, list a relative humidity greater than that created by the constant chamber dew point temperature of 57°F (14°C) , although many of these cities also exhibit a much lower average July nighttime low temperature of 68°F (20°C). An extensive analysis incorporating the 24-hour dry-bulb and wet-bulb temperatures should be performed to fully investigate the indoor comfort created by the night ventilation scheme.

A discussion of the energy savings for the night cooling tests and an analysis of the energy savings for the night ventilation test will be presented in a future paper.

CONCLUSION

An externally insulated massive test structure was capable of maintaining an "adequate" indoor 24-hour air temperature when cooling was provided only during the night hours. For extreme summer temperature cycles, exceeding those found in the United States, space cooling of such a building could be provided by night cooling using a mechanical cooling unit. For milder temperature cycles, such as those experienced in July for most of the United States, the night cooling could be provided solely by ventilation with outdoor air.

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Table 1. The Average Daily Air Temperature Extremes and Relative Humidity for Selected Cities in the Month of July

	High°F(°C)	Low°F(°C)	RH%	At
Albuquerque	91 (32.8)	66 (18.9)	36	11 am
Atlanta	87 (30.6)	71 (21.7)	64	1 pm
Chicago	81 (27.2)	67 (19.4)	55	12 pm
Dallas	95 (35.0)	75 (23.9)	50	12 pm
Denver	88 (31.1)	57 (13.9)	36	1 pm
Houston	94 (34.4)	71 (21.7)	55	12 pm
Los Angeles	76 (24.4)	62 (16.7)	68	10 am
Memphis	91 (32.8)	72 (22.2)	57	12 pm
Miami	89 (31.7)	75 (23.9)	64	1 pm
Minneapolis	84 (28.9)	61 (16.1)	56	12 pm
Nashville	91 (32.8)	70 (21.1)	58	12 pm
New York	85 (29.4)	68 (20.0)	55	1 pm
Omaha	90 (32.2)	67 (19.4)	45	11 am
Phoenix	105 (40.6)	75 (23.9)	29	11 am
Pittsburg	85 (29.4)	65 (18.3)	-	-
San Francisco	64 (17.8)	53 (11.7)	75	10 am
Seattle	76 (24.4)	54 (12.2)	66	10 am
St. Louis	89 (31.7)	67 (19.4)	58	12 pm
Washington, DC	87 (30.6)	69 (20.6)	52	1 pm

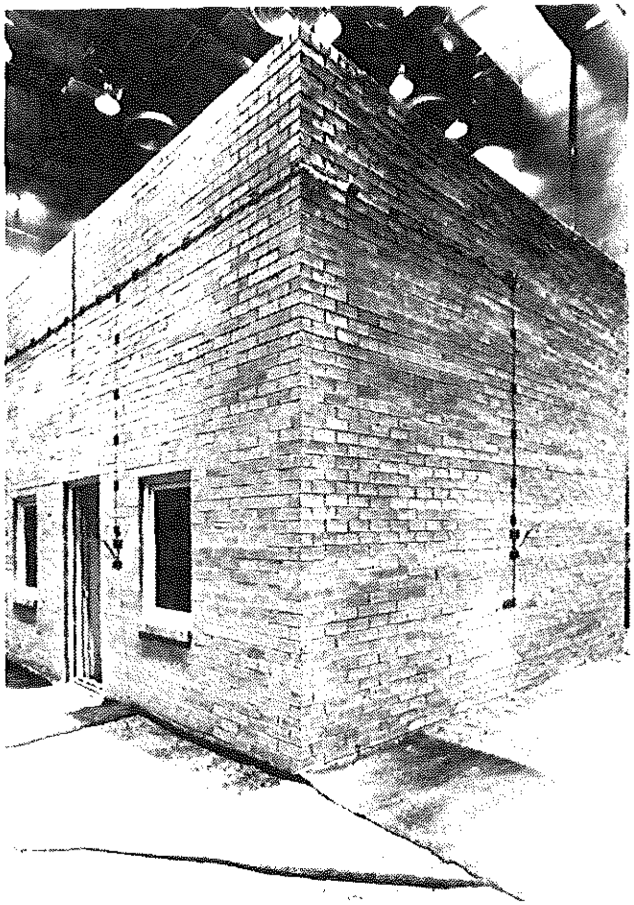

Fig. 1 A photograph showing the construction of the test structure

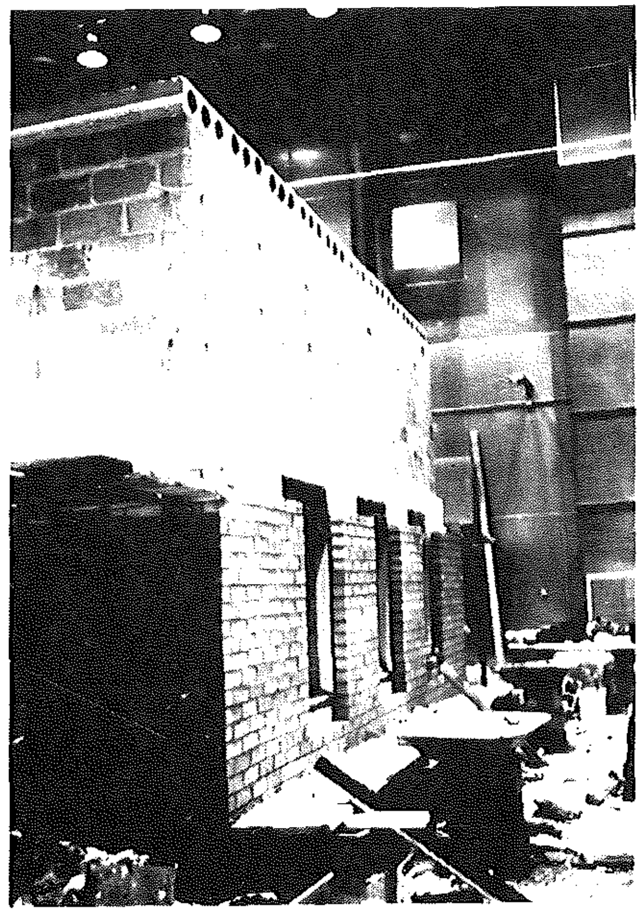

Fig. 2 A photograph showing the completed test structure

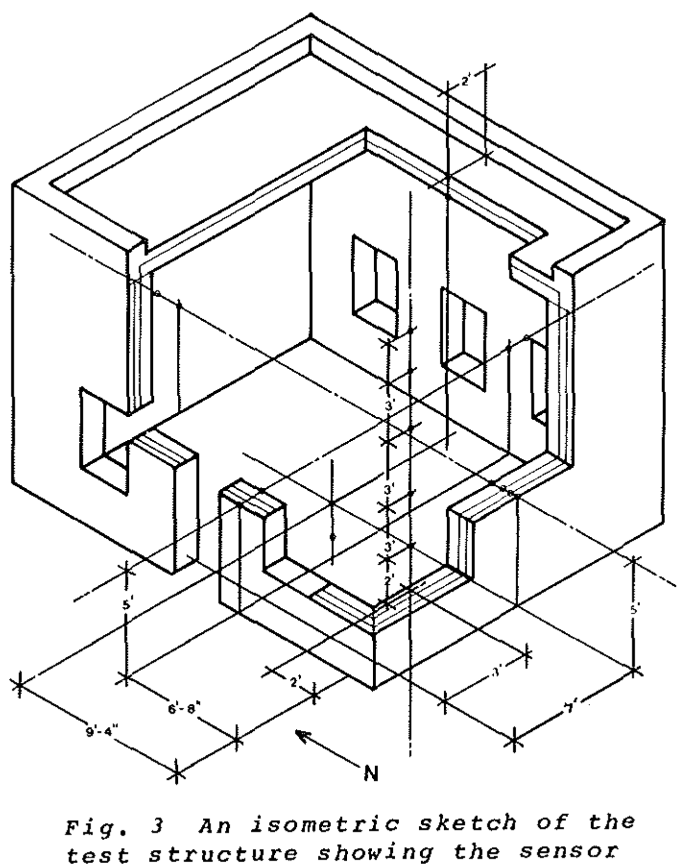

Fig. 3 An isometric sketch of the test structure showing the sensor locations

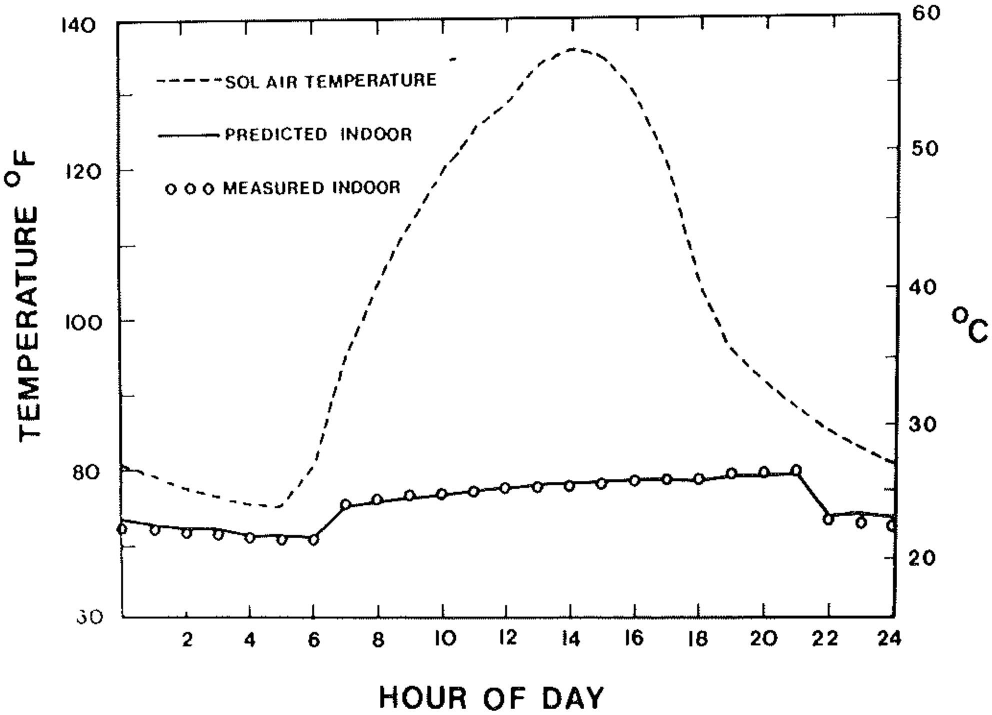

Fig. 4 Response of the test structure for the night mechanical cooling test; comparison of measured and predicted values

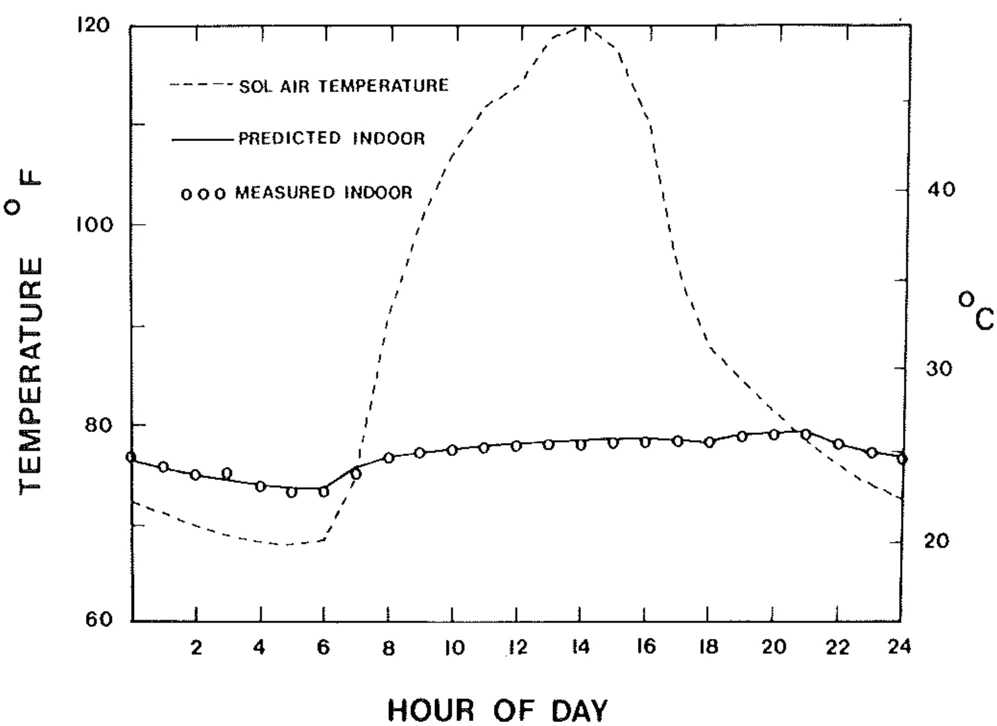

Fig. 5 Response of the test structure for the night ventilation test; comparison of measured and predicted values