BY ANDREW J. HOLSTEIN, EIT, AND DAVID R. BOHNHOFF, PHD, PE

BUILT FOR EFFICIENCY: A ROTATABLE GUARDED HOT BOX

Built for the needs of the post-frame industry

SAVING ENERGY, SAVING MONEY

A recent emphasis has been placed on energy conservation because of a combination of economic and environmental concerns. With operating costs typically constituting 80 percent of a building's life-cycle costs, relatively small investments in thermal efficiency up front can result in huge savings for owners over the life of a building. To take advantage of these market demands, manufacturers of building products promote their products with lofty statements of efficiency and impressive design values, often calculated by oversimplifying complex heat-transfer situations. These design values are therefore applicable only in certain situations and lead to many myths and misconceptions about the thermal performance of a building. To properly estimate the heat flow through a building's exterior shell, one must determine the overall thermal efficiency of the building's envelope, which comprises all the materials that physically separate the building's exterior and interior environments. Each of these materials may have a different level of thermal transmission, and the combination of materials may create complex modes of heat transfer (i.e., conduction, mixed convection, radiation). Heat transfer through the envelope therefore becomes non-uniform and three-dimensional, and the effect that air infiltration has on heat transfer compounds the issues. These factors make it extremely difficult to accurately calculate the heat flow through a build-

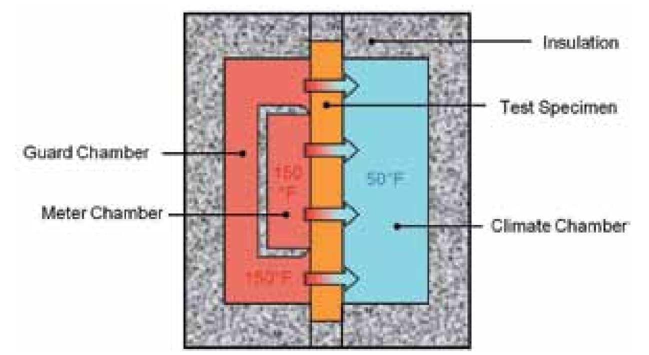

FIGURE 1. Section view of a guarded hot box

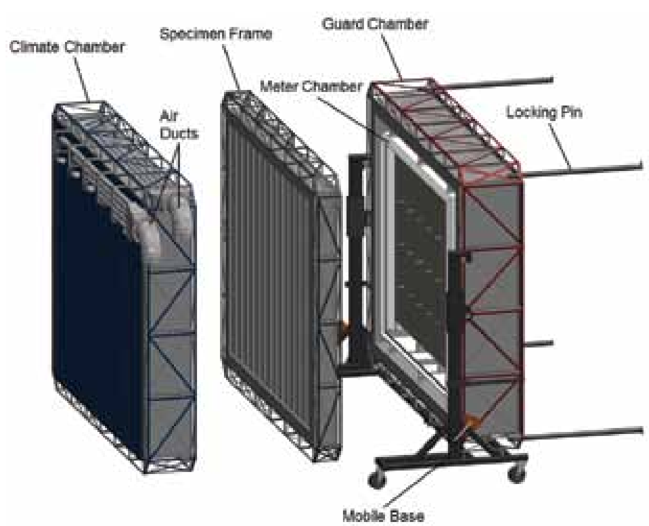

FIGURE 2. Design of final UW-Madison guarded hot box

ing's envelope using numerical means. Therefore, the best method for determining the overall thermal efficiency of a building's envelope is the large-scale testing of representative wall and roof sections side by side under laboratory conditions. This testing is done using an apparatus known as a *hot box*.

ROTATABLE GUARDED HOT BOXES

Researchers at the University of Wisconsin–Madison have undertaken the design and fabrication of a particular type of hot box referred to as a rotatable guarded hot box, or RGHB (**Figures 1, 2**). The main component of an RGHB is its meter chamber, a five-sided insulated box that is applied to the warm side of a test specimen. Air inside the meter chamber is heated to a steady-state temperature, and further energy input is monitored. An energy balance for the meter chamber shows that energy input must equal energy leaving the meter chamber through either the five sides of the chamber or the test specimen. To isolate the energy flow through the test specimen, the meter chamber is placed inside another chamber maintained at the same steady-state temperature. Because there is no temperature differential across the five meter chamber walls, there is no heat flow, and the meter chamber is "guarded" from heat loss; thus the outside chamber is referred to as a *guard chamber*. To test specimens over a greater temperature gradient, a climate chamber, which can be cooled and maintained at a lower steady-state temperature, is attached to the other side of the test specimen. In order to test roof sections as well as wall sections, the entire apparatus is mounted on a steel frame that allows it to rotate 360 degrees. Hot boxes of this type are referred to as *rotatable*.

PLANNED RESEARCH

Upon completion, the UW–Madison RGHB will be the only hot box apparatus in the United States affiliated with a public education institution. This affiliation will provide the public greater access to the test apparatus as well as its data. Through the collaboration of industry leaders and faculty from one of the nation's leading research universities, the UW–Madison RGHB will provide relevant building research for years to come. In addition, the UW–Madison RGHB is the only hot box apparatus in operation primarily dedicated to the analysis of thermal envelopes for buildings associated with food and with feed and fiber production and processing. These buildings, representing a variety of unique envelopes designed to cope with the high-humidity corrosive environments of the agriculture industry, have been largely ignored by previous hot-box testing programs. Because post-frame buildings are generally considered some of the most structurally efficient structures on the market today, it is vital that steps are taken to ensure that they come to be known for their energy efficiency as well.

METER CHAMBER

An integral part of the operation and accuracy of any RGHB is the concept of the energy balance control volume created by the meter chamber. In theory, any energy entering the meter chamber at steady state to power heaters and fans must be leaving through the test specimen. For this reason, careful attention was paid to ensure that the meter chamber walls would provide a sufficient boundary to heat and mass transfer, therefore simplifying the calculation of a test specimen's effective thermal resistance. The UW RGHB meter chamber was constructed of an internal frame of hot-rolled steel angle sheathed in three-inch-thick monolithic expanded polystyrene (EPS) blocks with a unit thickness thermal resistance of R-3.85 hr-F-ft^2/Btu-in, yielding a clear wall value of R-11.6 hr-F-ft^2/Btu. The EPS blocks were contoured for better air circulation, covered in a protective fiberglass-reinforced plastic (FRP) skin, and bolted to the internal steel frame using custom-made nylon threaded rods that reduce heat transfer through the meter chamber wall (**Figure 3a**).

The meter chamber is suspended within the guard chamber using a series of spring-loaded supports (**Figure 3b**) bolted directly to the internal steel frame with nylon threaded rods. When the chambers are assembled and secured using the corner locking pins, the meter chamber is displaced into the guard chamber, compressing the springs and ensuring a uniform force is applied to the chamber seal. The supports are adjustable in all three dimensions, and the springs may be precompressed if additional sealing pressure is required.

FIGURE 3. (a) Meter chamber and **(b)** meter chamber spring support

FIGURE 4. Climate (blue), specimen (black) and guard (red) trusses lined with steel panels

FIGURE 5. Installation of **(a)** specimen frame insulation around support beam, and **(b)** protective FRP skin

GUARD AND CLIMATE CHAMBERS

The guard and climate chambers were designed with exceedingly stiff and light space trusses, which allow for lifting and rotating the apparatus with minimal deflection. After construction, the trusses were lined with 20-gauge steel sheets plug welded every nine inches. This lining increased the truss stiffness, provided a suitable surface for attaching the insulation and protected the chamber from accidental damage. Corrugated steel panels, reinforced with thin steel box tube, were used to enclose the large open backs of the trusses (**Figure 4**).

All five walls of the chambers were then lined with six-inch-thick blocks of EPS insulation, yielding a clear wall R-value of 23.1 hr-F-ft^2/Btu. Maximum block width was restricted to four feet by the supplier, and therefore the back was formed from three separate blocks. Foam blocks were trimmed to fit snugly and adhered to the steel lining with a moisture-cured polyurethane adhesive suitable for bonding EPS to steel. All seams were sealed with expanding polyurethane crack sealant, and the front sealing surface was covered with an FRP skin to promote sealing and protect the foam. After installation, all interior surfaces were painted a matte black to mimic the radiative properties of a black body. Finally, a duct system was installed in the climate chamber to remove warm air from the chamber and replace it with air cooled by an independent air conditioning system (Figure 2).

DUAL SPECIMEN FRAMES

To promote the efficient testing of specimens, two independent support frames were constructed to hold the 9.5 x 12.5 x 1-foot test specimens. In this manner, one test specimen may be tested while the next is constructed and instrumented. Specimen frames were designed to align with the guard and climate chambers and be secured to them using four corner locking pins. A hollow plywood box beam was attached to the specimen frame truss to facilitate specimen attachment. The beam (**Figure 5a**), which is surrounded by—and filled with—high-efficiency Neopor insulation (BASF 2012) with a unit thickness R-value of 4.5 hr-F-ft^2/Btu-in, allows an unlimited array of specimen geometries to be securely and efficiently attached, while mini-

FIGURE 6. (a) Mobile base and **(b)** storage and transport cart designs

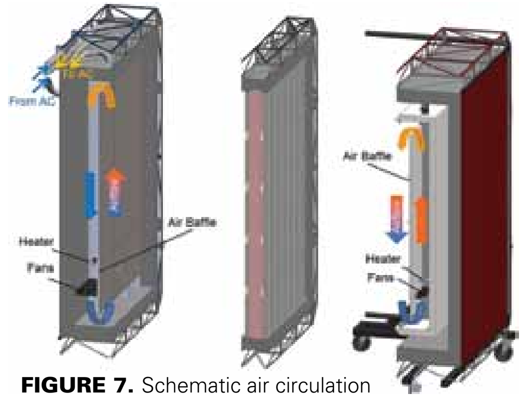

FIGURE 7. Schematic air circulation and conditioning system

mizing thermal transfer through the specimen frame. The specimen frame foam was also wrapped in a protective FRP skin that provides a smooth, hard sealing surface (**Figure 5b**).

A BASE BUILT FOR MOBILITY

From the beginning, the UW–Madison RGHB was designed for mobility. The crux of this mobility lies in its mobile base, which allows the apparatus to be easily moved about its shared laboratory space to maximize floor space when not in use, simplifies the transport of the apparatus to other research venues and facilitates chamber rotation through a combination of hand and electric winches. The mobile base consists of a stout welded frame with two uprights, along which two pivot pin carriers ride (**Figure 6a**). These carriers support the main pivot pin welded into the guard chamber and are raised and lowered using a manual winch system. Once the chamber assembly has been winched to the rotation height, a small electric winch installed on the bottom of the base frame rotates the chambers by drawing in or letting out a tether attached to the guard chamber truss. In this manner a single worker can raise, rotate and lower the chambers with minimal effort.

CARTS AND ALIGNMENT

Besides providing increased mobility, the base design provides a continuous horizontal reference plane that is used to align the chambers for attachment. In addition to the mobile base, three transport and storage carts were fabricated (**Figure 6b**), one for each specimen frame and one for the climate chamber. To open the apparatus for specimen loading, the three attached trusses (climate chamber, specimen frame and guard chamber) are lowered onto the mobile base in a vertical orientation. With all three trusses supported by the base, the four corner locking pins are removed, and the individual trusses may be separated with the use of their respective carts. First, the climate chamber cart is aligned with its truss and lifted into position using a hydraulic pallet jack; once the pallet jack raises the truss clear of the mobile base, it is drawn away from the base and lowered until the transport cart is supporting itself and the truss. A set of safety bars (Figure 6b) that lock the truss securely to the cart and prevent tipping during transport are then attached. The climate chamber is set to the side, and the process is repeated for the specimen frame being removed from the apparatus. A new specimen frame is then aligned on the mobile base by reversing these steps, the climate chamber is added and the four corner pins draw the assembly tightly together. The assembled chambers may then be tested as is, or raised and rotated to any desired testing orientation.

CONDITIONING AND CIRCULATING AIR

Because the theory behind an RGHB relies on each chamber remaining at a steady-state temperature, the conditioning and circulation of chamber air are crucial for accurate operation. (**Figure 7**) shows a general schematic of the airflow patterns in each RGHB chamber. Each chamber is separated into a series of convective loops by a large steel baffle and a series of ribs. Airflow in each loop is then generated in the direction of natural convection. That is to say, hot air at the top of the meter chamber gradually gives up some of its energy to the test specimen and cools; as this happens, the air becomes less buoyant and sinks to the bottom of the chamber. At this point, the cool air is drawn by a cluster of small axial fans up the back of the air baffle, where it is returned to the chamber set-point temperature by finned heaters. The procedure is similar in the climate chamber; cold air in contact with the specimen surface gains energy, becomes less dense and rises to the top of the chamber. At this point, a portion of the warm air is drawn off by the ducting system and sent to a mobile air conditioning unit. This unit cools the air below the climate set-point temperature and returns it through a distribution duct on the back wall of the chamber (Figure 7). This cold air mixes with the main flow and is drawn down the back side of the air baffle by small axial fans. When it reaches the bottom, the temperature is fine-tuned to the exact set-point temperature by finned heaters.

CHAMBER PRESSURIZATION

A major phenomenon affecting the effective thermal performance of a building envelope is the degree to which air infiltration occurs. To measure this effect, air infiltration is induced by a static pressure differential applied to the test specimen. This differential is created through the use of a pressurization fan and reheat chamber (**Figure 8**). Air is drawn out of the climate chamber by the pressurization fan, raised to the meter chamber

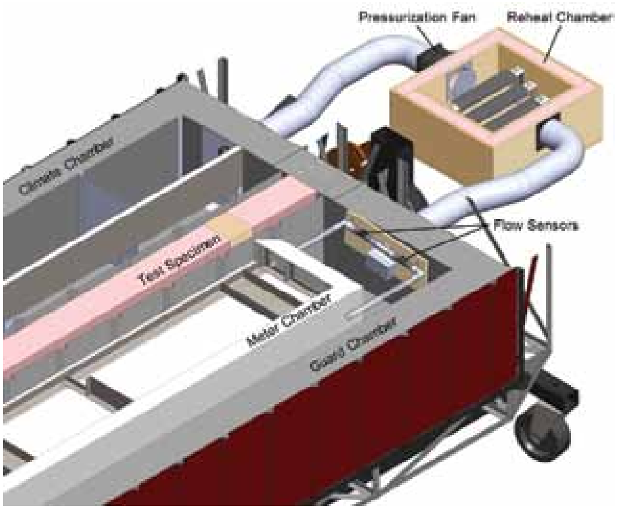

FIGURE 8. Section view of assembled chambers showing pressurization system

set-point temperature in the reheat chamber and distributed to the meter and guard chambers simultaneously. This setup ensures that the meter and guard chambers will have identical pressures, thereby limiting any meter chamber air exfiltration to that passing through the test specimen. Two flow sensors are positioned to measure the air flowing into each chamber.

SENSORS AND CONTROLS

To maintain and record the steady-state conditions required for an RGHB to operate accurately, the UW–Madison apparatus was designed with an array of more than 300 temperature, air speed and pressure sensors. These sensors, in turn, are connected to dozens of wireless sensor boards that digitize the signal within inches of its sensor, increasing system flexibility while minimizing system error, thermocouple material cost and insulated envelope penetrations.

Readings from these sensors are relayed wirelessly to a centralized data acquisition and control computer running a custom-designed LabVIEW software program (National Instruments, 2014). Readings regularly logged by the program include energy consumption, chamber pressures and flow rates, and surface and air temperatures. In addition to monitoring the vital chamber statistics, the system varies heater and fan output, calculates and records key variables and determines the completion of experimental objectives. This system allows the efficient conduction of accurate thermal envelope studies using a minimum of human interaction.

SUMMARY

Upon completion, the UW–Madison RGHB will be a first-of-its-kind research apparatus dedicated to the large-scale study of the thermal efficiency of the post-frame building envelope. Capable of testing specimens up to 9.5 x 12.5 feet, the apparatus will explore the effect of air infiltration through the application of a static pressure differential across the specimen. A unique mounting system allows the apparatus to quickly load specimens and rotate on its horizontal axis to test a variety of wall and roof specimens at any orientation. Testing efficiency has been optimized throughout the apparatus, including the simplified rotation procedure, the fabrication of a second test specimen frame that allows parallel specimen fabrication and testing, and the incorporation of an autonomous computer control system.

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