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DYNAMIC THERMAL PERFORMANCE MEASUREMENTS OF CLAY BRICK MASONRY

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ABSTRACT
The dynamic thermal performance of a clay brick masonry wall system was measured using an innovative hot box design. Heat flux sensors were used extensively to measure heat flows and heat storage due to the thermal mass in several stud wall systems. The performance of this hot box was validated by testing a number of test panels with known thermal properties. This study primarily focused on measuring the contribution of brick veneer and the air space between the veneer and sheathing to the thermal performance of the wall system. The wall panels were exposed to a standard set of exposure conditions that included both steady state temperature differences and dynamic exposures. The R-value and effective heat capacity were measured for each wall system using these standard exposure conditions. Thermal decrement and lag were also measured for the wall systems during dynamic measurements. A number of thermal performance metrics for the wall systems were analyzed and discussed. Clay brick veneer was found to significantly reduce the flow of energy through the wall system during dynamic cycling with both open and closed weepholes when compared to the same wall system with no veneer. Steady state measurements did not adequately capture the benefit of the reduction in energy flow through the wall due to the thermal mass provided by the veneer.

KEYWORDS: *clay brick, R-value, dynamic thermal performance, hot box, thermal mass, weepholes*

INTRODUCTION
In this study both the steady state (constant temperature difference) and transient or dynamic (continuously varying of cyclic temperature difference) thermal performance of a clay brick veneer

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alone (no studs), wood stud wall alone (no brick), and a complete clay brick veneer and wood stud wall were compared using a specially designed hot box [1,2]. Thermal conductance and R-Value were determined during steady state measurements, while the effect of thermal storage or heat capacity was measured during dynamic measurements.

Transient one dimensional heat flow through a wall can be described by the following differential equation:

$$\frac{dT}{dt} = \alpha \frac{d^2T}{dx^2} \tag{1}$$

Where T is temperature, t is time, x is distance or thickness and α is a material property known as thermal diffusivity. This equation is the most basic form of an equation that explains the change in temperature as a function of time for a material with a defined thickness due to an applied temperature difference. The thermal diffusivity, α, of the wall system depends on the type of materials used in the wall, their thickness and placement.

Thermal diffusivity is a function of thermal conductivity (k), the density (ρ) and the heat capacity or heat storage (C_p) of the wall according to the following equation.

$$\alpha = \frac{k}{\rho C_p} \tag{2}$$

The implication of this equation is that the actual real-world thermal performance of a wall system is dependent on all three characteristics. Typically, the thermal performance of a wall is only characterized by the R-value which is another way of reporting the thermal conductivity [3]. The thermal conductivity is typically measured by subjecting the system to a constant temperature difference and does not reflect real world conditions where the temperature changes dynamically throughout the day. This term is typically used to describe thermal performance because it is the easiest to measure, understand and apply. The test method described in ASTM C 518 is commonly used to measure the steady state performance of materials while the procedure described in ASTM C 1363 is used to measure the steady state performance of wall systems [4,5].

In conditions that are closer to actual weather patterns, with dynamically cycling exterior temperatures, it is possible that a wall with a high thermal conductivity (low R-value) will have significantly increased performance if the density and heat capacity terms are large [6]. Clay brick, typically have a higher thermal conductivity (lower R-value) than insulating materials, but have a higher density and heat capacity that can potentially offset the effect of the thermal conductivity. In summary the actual thermal performance of a wall is dependent on not just the thermal conductivity (R-value) but also the density and heat capacity [7]. The terms thermal mass, thermal storage, thermal inertia, etc. are commonly used to describe the effect of heat capacity and density on dynamic thermal performance.

TEST METHODS

In this study, a hot box was designed and constructed to measure steady state properties like the majority of hot boxes, but has also been expanded with additional sensors that allow for dynamic thermal performance measurements on wall systems [1,2,5]. A calibrated heat flux meter as described in ASTM C 518 was used to confirm heat flux measurements of this hot box [4].

The hot box used in this study was designed to accommodate a 6′×8′ (1.83 m × 2.44 m) test panel. The hot box consisted of a climatic (external) and metering (internal chamber) that were capable of independent air temperature control [2]. A variety of heat flux pads and thermocouples were used to quantify heat flow, chamber air temperatures and surface temperatures on both the climatic and metering sides of the test panel. This design and instrumentation allowed for both dynamic and steady state measurements [2,8,9] of the thermal performance of wall systems. Typical instrumentation is shown in Figure 1.

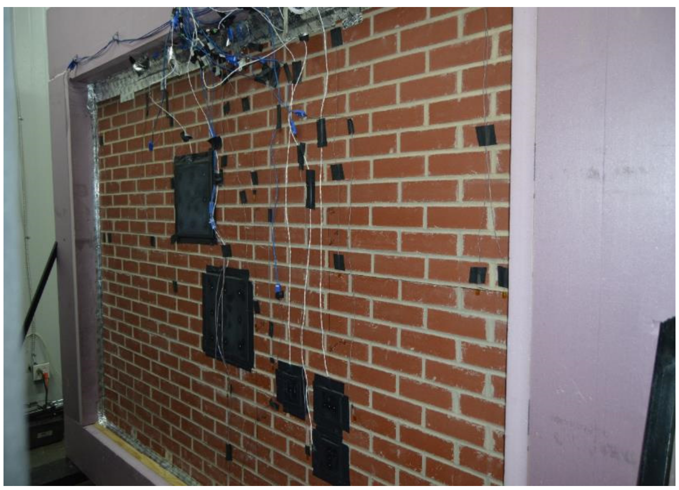

Figure 1: Sensors on Brick Veneer (exterior of full wall system)

Four wall configurations were tested in this study. The walls included brick veneer with no backup, and a stud wall that included house wrap, OSB sheathing, 2″×4″ studs with insulation and finished with gypsum board (no veneer). Finally a complete wall system that included the brick veneer, an air space and then the stud wall system described previously was also tested. A cross section of the complete wall system is shown in Figure 2. The goal of this study was to not only measure the thermal performance of the complete clay brick veneer wall system, but also to measure the performance of the components (veneer only and stud wall) to determine the contribution of each of the parts to the overall thermal performance. For the complete wall system, two configurations were tested. In one configuration the weepholes were open which theoretically allow airflow in the cavity. In the second configuration, the weepholes were sealed to compare to the wall with open weepholes.

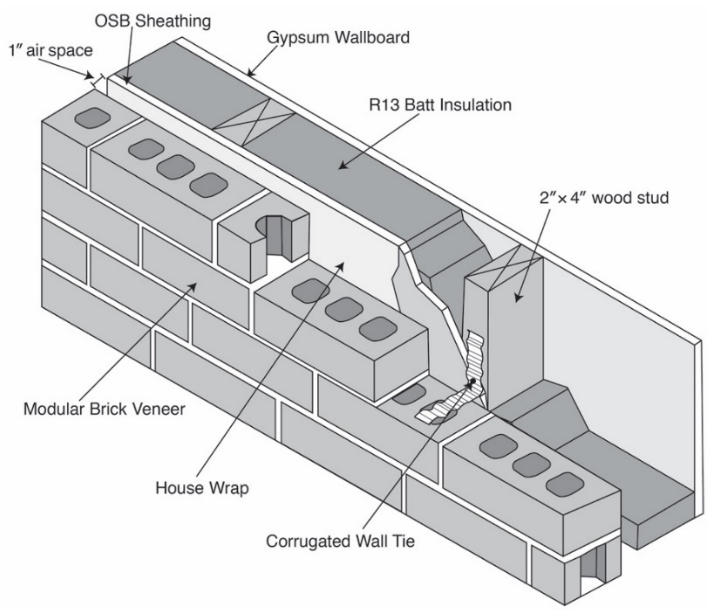

Figure 2: Brick Veneer Wall System Cross Section

A stepped temperature cycle was utilized to measure both the thermal conductivity and the heat capacity (storage) of the wall systems [8, 10]. The step cycle consisted of an initial condition where the surface temperatures were balanced on both sides of the test panel to achieve a steady state condition with essentially zero heat flux through the wall. The air temperature of the climatic (brick veneer) side was increased to create the desired temperature differential (Δ10°C or Δ20°C). The difference between the heat flux in and the heat flux out of the wall during the transient or equilibration period was used to calculate the heat capacity [11]. Once steady state was re-established after cycling, the thermal conductivity, thermal conductance or R-value was measured. The density of the wall system was calculated from weights and dimensions of the test panels. Examples of the heat flux into and out of the wall are shown in Figure 3 while the difference between the two which was used to calculate the heat capacity is shown in Figure 4.

RESULTS AND DISCUSSION

A summary of thermal property data is shown in Table 1. Heat flux and thermocouple data was used to calculate the data reported in Table 1 [2,10]. In the first set of measurements for this wall system, the weepholes and top of wall were left open. In a second set of measurements, the weeps and the top of wall were sealed. This was done to investigate the assumption that open weepholes may allow significant flow in the cavity which results in higher heat flow that undermine the thermal performance of the brick veneer. Further study of airflow in the cavity has been conducted but is beyond the scope of this paper.

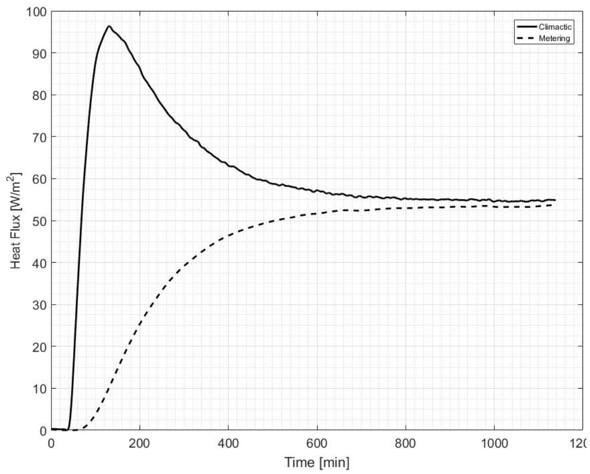

Figure 3: Heat flux in and out of a veneer only test wall during temperature change.

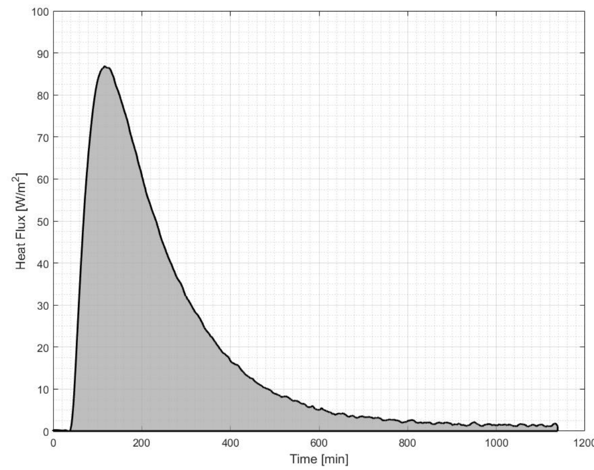

Figure 4: Heat flux difference for veneer only test wall during temperature change

Table 1: Thermal Performance Data

Test Panel	Units	Veneer Only	Stud Wall	Veneer/Stud –Open Weeps	Veneer/Stud –Closed Weeps
Thermal Conductance	W/m K	6.396	0.473	0.438	0.435
R_{SI}		0.156	2.115	2.283	2.301
R		0.888	12.015	12.969	13.072
Heat Capacity	J/Kg K	814.7	894.4	447.3	458.2
Density	Kg/m^3	2028	165	1244	1244
Energy Absorbed during Step Measurement	J/m^2	1,225,408	288,865	2,246,983	2,307,206

Based on the data reported in Table 1, it is clear that the brick veneer by itself had a significantly higher thermal conductance than the stud wall, as would be expected, but the brick also stores a significant amount of energy based on the density and heat capacity. Adding the veneer to the stud wall, which contains insulation between the studs, improved the R-value relative to the brick veneer by itself. The addition of the veneer and air space to the stud wall resulted in further improvements to the R-value.

The heat capacity (storage) of the stud wall appears to be higher than the veneer and stud wall systems despite the fact that the veneer and stud wall absorbed significantly more energy than the stud wall by itself. This is due to the differences in the density of the walls and illustrates the interdependence of the thermal properties mentioned previously [3]. Although concern has been raised that open weepholes significantly increase airflow in the cavity, little difference in airflow was found between the wall with weepholes (open head joints) and the wall with no weepholes. In addition, the difference in thermal performance of the walls with and without weepholes was negligible.

The amount of energy absorbed by the whole wall, which is the difference between the heat flow in and the heat flow out, was an order of magnitude higher for the veneer and stud walls compared to the stud wall by itself. A comparison of the amount of energy absorbed by each wall (difference between heat flow in and heat flow out during a temperature change) is shown in Figure 5 as an alternate means of comparing the thermal performance. The amount of energy absorbed (reported in Table 1) is the area under the curves shown in Figures 4 and 5. The wall systems containing brick resulted in increased energy storage during cycling due to the density and thermal mass of the clay brick veneer which illustrates the benefit of thermal storage by the brick veneer. In other words, the brick store energy during a temperature change and reduce the amount of energy that is transferred through the wall [3,7]. It should also be noted that the storage for the stud wall was very small when compared to the veneer and stud wall energy storage. The width of the peak also illustrates the amount of time that the wall is absorbing energy and limiting the amount of heat that is admitted into the interior of the wall system.

In addition to the step cycles used to measure the thermal conductance and heat capacity, the wall systems were subjected to further cycling in this study. There have been a number of previous studies of thermal performance in simulated day/night cycles [9,12]. One of the most widely used simulated day/night cycle is the so called "sol-air cycle" that was first described in a National Bureau of Standards publication in 1972 [12]. An example of the sol-air cycle is shown in Figure 6. The cycle represents a very extreme climate with a peak temperature of approximately 40°C (104°F) and a minimum temperature of approximately 10°C (50°F) over a 24-hour period. The air temperature of the exterior or climatic side of the wall was subjected to this temperature cycle while the air temperature of the interior or metering side was kept at a constant 24°C (75°F) in these thermal cycling experiments.

To illustrate the benefit of thermal mass during dynamic cycling experiments, the lag and reduction or decrement have been used [9]. The lag is the time difference between the peak temperature or heat flow from the climatic (exterior) surface to the metering (interior) surface. The reduction or decrement is the decrease in the magnitude of the surface temperature or heat flow between the climatic (exterior) surface to the metering (interior) surface.

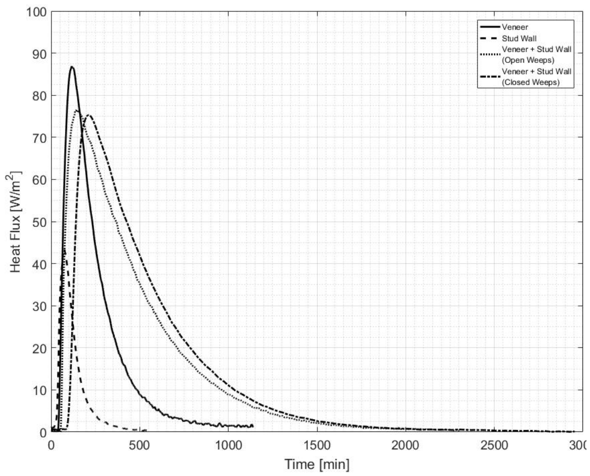

Figure 5: Comparison of Heat Flux Differences

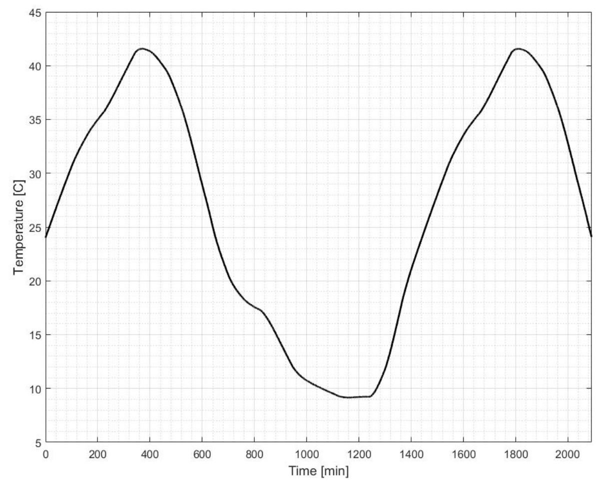

Figure 6: Sol-Air Temperature Cycle

A comparison of the lag and reduction or decrement for temperature and heat flow for all of the tested walls are reported in Table 2 [9]. The brick veneer only wall system had the lowest lag due to its higher thermal conductance. The stud walls with brick veneer showed a higher reduction in heat flux than the stud wall by itself which means that the brick veneer storing and reducing the amount of the energy that would normally pass through the wall system. This reduction is consistent with the trends shown in Figure 5 and Table 1. The difficulty related to the interpretation of the data in Table 2 further illustrates the interrelation of the thermal conductance, heat capacity (storage) and density of the wall systems [3]. The buffering effect of the brick veneer reduces the amount of work that the HVAC system would have to do to maintain the desired interior temperature [3]. These dynamic tests, which are better simulations of real world conditions, highlight the thermal benefit of the brick veneer.

By subjecting all of the wall systems to the same standard exposure condition with the sol-air cycle, the actual amount of energy that reaches the metering side or interior of the structure for each of the tested wall systems could be directly compared. An example comparison of the metering wall heat flux (net heat flux) is shown in Figure 7. The lower peak magnitude and shift to later times for the veneer stud wall systems further illustrate the effect of thermal mass on reducing heat flow during thermal cycling. It should be noted that the magnitude of this effect is a function of the thermal cycle that is used during testing [7]. Cycles with large temperature swings, such as the sol-air cycle, increase the benefits of thermal mass by reducing heat flow, while the effect of thermal mass is significantly diminished when there is little to no temperature swing.

Table 2: Comparison of Lag and Reduction for Temperature and Heat Flow

Test Panel	Units	Brick veneer Only	Stud Wall	Brick Veneer/Stud – Open Weeps	Brick Veneer/Stud – Closed Weeps
Heat Flux Lag	Minutes	142	181	290	275
Surface Temperature Lag	Minutes	80	181	179	160
Heat Flux Reduction	W/m²	33.9	19.0	66.8	66.9
Surface Temperature Reduction	°C	6.3	15.7	10.7	10.5

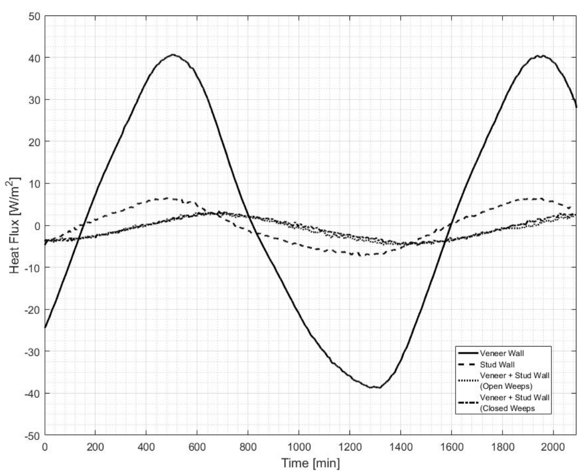

Figure 7: Metering Wall Heat Flux Comparison

Due to the fact that the sol-air cycle used in this study has periods of both high and low temperature, both positive and negative heat flows on the metering (interior) wall were observed as indicated in Figure 7. Based on the trends shown in Figure 7, the brick veneer by itself allows the most heat to pass through to the metering (interior) wall and results in a considerable swing in surface temperature on the interior wall as would be expected based on the thermal conductance reported in Table 1 for this wall system. The heat flow and temperature swing on the interior wall was much lower for the stud wall by itself, which contained insulation between the joists and had a lower thermal conductance as a result. Adding the brick veneer to the stud wall further reduced the heat flow and temperature swing at the interior surface. Adding the brick veneer also significantly delayed the peak interior surface temperature due to the damping effect of the brick's thermal mass. The condition of the weepholes (open or closed) had little effect on the net heat flow suggesting there is minimal air flow in the cavity even when open head joint weepholes are installed.

Finally, the total amount of energy that passed through the metering (interior) wall was compared for both positive heat flow (exterior to interior) and negative heat flow (interior to exterior). In other words, heat flowed toward the interior during the hottest part of the sol-air cycle due to the temperature difference across the wall system which was referred to as positive heat flow. Conversely, heat flowed toward the exterior during the colder part of the sol-air cycle which was referred to as negative heat flow. The power required to maintain a constant interior temperature for each of these periods was determined by integrating the heat flow as a function of time to determine energy usage. A numerical summary of this comparison is shown in Table 3.

Table 3: Energy Transfer to the Interior (metering wall)

Test Panel	Units	Brick Veneer Only	Stud Wall	Brick Veneer/Stud – Open Weeps	Brick Veneer/Stud – Closed Weeps
Metering Wall Energy Transfer (Positive Heat Flow Direction)	J/m²	961,670	136,360	70,310	62,101
Metering Wall Energy Transfer (Negative Heat Flow Direction)	J/m²	-1,116,200	-218,040	-136,200	-131,610

The comparison of the total amount of energy transferred during parts of the sol-air cycle reported in Table 3 indicate the potential for significant reductions in the amount of energy required to maintain a constant interior temperature for the brick veneer and stud wall systems compared to the stud wall and the brick veneer by itself. A reduction in heat flow due to the brick veneer of up to 48% was observed for the wall system with open weepholes relative to the stud wall system with no brick veneer and air space. It is important to note that this reduction is a function of the sol-air cycle used for the climatic exposure in this study. The actual effect of the thermal mass is dependent upon actual climatic exposure [3,7]. While the cavity with open weepholes did result in slightly higher energy transfer, both of the brick veneer and stud wall systems resulted in substantially reduced energy flow relative to the stud wall by itself for this climatic cycle. These results strongly suggest that any assumption that brick veneer does not contribute to the thermal performance of the wall system is incorrect. Further studies regarding the magnitude of flow in the air cavity and its effect on thermal performance are ongoing.

The heat flow comparison in Table 3 also indicates that the effect of the thermal mass is also a function of the direction of heat flow. A higher degree of heat flow reduction was observed for the brick veneer and stud wall systems in the positive heat flow (exterior to interior) direction. Several studies have also identified that the placement of the thermal mass influences the thermal performance of the wall system [7]. The thermal performance of brick veneer and stud wall systems appears to be better in the summer versus the thermal performance in the winter during dynamic cycling. This finding indicates that further optimization of the wall system for various climates by strategic placement of the thermal mass and insulating components is possible.

CONCLUSIONS

In conclusion, this study demonstrated that the thermal performance of masonry should not be described by a single number (such as R-value). Dynamic measurements, illustrate the thermal mass benefits of brick veneer wall systems where significant reductions in energy flow relative to an insulated stud wall were found. Future research will include continuing to develop modelling capabilities and investigating other wall systems and wall features. The main conclusion of this research is that brick veneer construction provides much higher levels of thermal performance than previously indicated, when tested in dynamic or thermal cycling conditions that are much closer to actual conditions than those used in steady state testing.

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