DYNAMIC SOLAR HEAT GAIN COEFFICIENT: EXPERIMENTAL EVALUATION OF THE OPAQUE PORTION OF A CURTAIN WALL SYSTEM

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ABSTRACT

The Solar Heat Gain Coefficient (SHGC) of the opaque portion of a curtain wall system has been determined experimentally. The curtain wall system under investigation consists of wall panels with structural exterior glazing. A 5- inch thick drywall was built in place. This steel stud wall, insulated with fiberglass and sheeted with gypsum board, is backed up against the shadow box of the curtain wall panel, see Fig. 1.

The examined building is located on a university campus in the arid climate of the Northern edge of the Sonoran desert. A monitoring system was set up to measure temperatures, solar radiation, and heat flux data. The data show that the temperature in the sealed air cavity of the curtain wall section (the shadow box) peaked above 200 °F. The air temperature in the shadow box frequently reached 95 °F above the interior wall surface when the wall was exposed to solar radiation. The SHGC calculated from the acquired data was significantly higher than the SHGC used in a computer simulation performed during the design phase. It was also found that the SHGC fluctuates with the temperature elevation in the shadow box. This phenomenon is characterized as a dynamic solar heat gain coefficient.

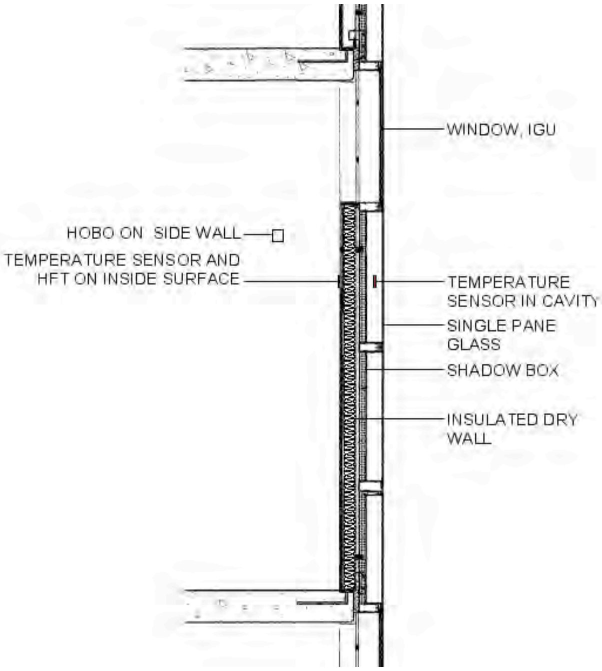

Fig. 1: Section cut through the curtain wall system.

1. INTRODUCTION

This paper reports on a research project that focuses on experimental evaluation of the SHGC of the opaque portion of a curtain wall system found on the Lattie F. Coor Hall, a new office and classroom building at the Arizona State University (ASU) Tempe Campus.

The building was completed in 2003. As the building design scheme was presented during a lecture at ASU, the architect explained that the design was based on a metaphor of “a gigantic block of ice resting on large boulders in the desert”. In response to a commentary from the audience that this might become “a very hot block of ice”, members of the design-build team claimed that the building meets ASHRAE Standard 90.1. This claim is founded on data from building energy computer simulations using the DOE2 calculation engine. Since the DOE2 program sees an exterior wall element either as a window or an opaque wall, the opaque insulated portions of the curtain wall were simulated as windows. The R-value of this “window” was set at a high value (R-19), reflecting the assumption that the “shadow box” was insulated with polystyrene and the interior dry wall was insulated with fiberglass insulation, as specified. The Shading Coefficient (SC) of this “window” was set at a very low value (0.03), reflecting an assumption that only a few percent of the incoming energy flux from solar radiation would reach the interior.

When the building was completed, an opportunity presented itself to examine the opaque portion of the curtain wall - as built. The purpose of the investigation was to verify – or revise - the R-value used in the computer simulations and to calibrate the solar heat gain coefficient SHGC.

2. RESEARCH DESIGN

An opaque panel on the west facing exterior wall on the sixth floor was investigated. The panel is positioned between two transparent portions (windows) of the curtain wall, as seen in Fig. 2

Fig. 2: The curtain wall system seen from the outside on the west side of the building. A temperature sensor was lowered into the air cavity through a 1/4 inch hole at position 1. The tip of the sensor was placed at position 2.

The second part of the experiment involved an attempt to determine the energy flux through the opaque glass and wall assembly. A Silicon Pyranometer Smart Sensor measures solar radiation incident on the glass. This instrument was placed at the Solar Lab on the roof of the North Architecture building, a few hundred feet away from the building under investigation. A Heat Flux Transducer (HTF) was placed on the interior side of the dry wall. This instrument measures energy flux going out from or coming in through the wall assembly. Ambient air temperatures were extracted from local weather data. The thermal behavior of the wall assembly has also been documented using infrared photography, as seen in Fig. 3.

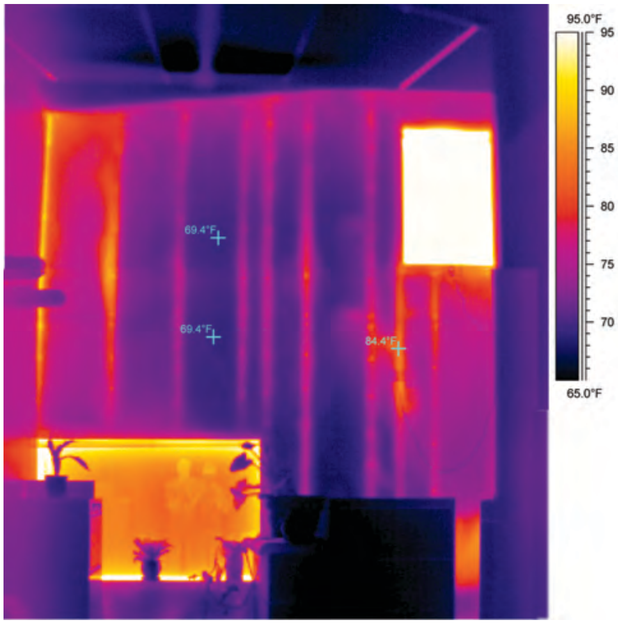

Fig. 3: Thermal image of the same wall as seen from the interior. Thermal bridges are seen, resulting from the thermal conductance of the steel studs and possibly also as a result of imperfect installation of the fiberglass insulation.

3. METHODS

Temperature data were recorded on to a HOBO™ U-12 data logger for extended periods of time during February - April 2005, August - September 2005, and November 2005 - February 2006. This data logger was started again in March 2006 and logs continuously. Room air temperature and relative humidity data are recorded at eight feet above finished floor. Two external TMC6-HD sensors record air temperature in the cavity of the curtain wall and surface temperature at the inside surface of the dry wall.

Data acquisition from the Pyranometer and the Heat Flux Transducer started in early March 2006. The HFT was placed at the surface of the dry wall, just above the surface temperature sensor, about 16 inches below the clerestory window and lined up with the left edge of this window, see Fig. 3.

While the data from the Silicon Pyranometer Smart Sensor were logged on to a HOBO Micro Station, an attempt to log data from the HFT on to a second Micro Station failed. With a calibration constant of 23 Btu/h-ft2, the HFT will typically put out signals in the 0.1 - 1.2 mV range. The HFT was first connected to a Micro Station via a 12-Bit 0-5 Volt Input Adapter. Since this volt adapter has a resolution of 0.6 mV, the logger would not record the fine resolution of the HFT signal. A Radio Shack Multi-meter was then used to manually record the mV signal from the HFT.

As an alternative to recording the heat flux by means of the HFT, heat flux can also be calculated when the R-value of the inside air film and the temperature differential from the inside surface to the interior air are known. ASHRAE Fundamentals lists the thermal resistance of the inside air film as R-0.68 (1). This value is commonly used and was derived from experimental data. As the temperature of the inside surface goes up during heat gain conditions, the heat transfer from the inside surface to the indoor air will be a product of increased convection and radiation. The R-value should therefore be lower during periods of significant heat gain through the wall.

We looked at the actual heat flux measured with the HFT on March 7, 2006 and compared the heat flux to the ΔT from the inside surface to the indoor air temperature, as measured by the HOBO U-12 logger. At 8:40 AM, we had a negative heat flux (heat loss) of Q=1.15 Btu/h-ft2. The ΔT at that same time was 0.777 °F. This produces an air film R-value of 0.68 using the formula $R=\Delta T/Q$ and assuming an area unit of one square foot. This indicates that the HFT is producing accurate results.

The same calculation was repeated for three points in time when heat gain occurred: 3:00 PM, 4:40 PM, and 5:15 PM. We got the following results, where T2 is the interior wall surface temperature:

8:40 AM	R=0.68	T2=72.2 °F
3:00 PM	R=0.56	T2=77.6 °F
4:40 PM	R=0.47	T2=92.1 °F
5:15 PM	R=0.46	T2=93.5 °F

With this established relationship between the inside air film R-value and the inside surface temperature (or ΔT), we can now calculate the heat flux for days when no experimental data from the HFT are available.

4. LIMITATIONS

The position under the clerestory window where the temperature sensor and the HFT were placed could well be a “hot spot”, as indicated in the thermal image in Fig. 3. The data acquired from these two instruments might possibly represent an extreme condition.

A second surface temperature sensor will therefore be installed and placed directly under the center of the clerestory window where the thermal conductance might be lower. The second sensor will provide data that can be used to assess the impact of the sensor placement on the validity of the data.

5. FINDINGS

The R-value of the entire wall assembly including the exterior glass and the sealed air cavity (shadow box) was determined through calculation using the formula $Rt= (\Delta Tt*Riaf)/\Delta Tiaf$, where Rt is the total thermal resistance, ΔTt is the temperature differential between outdoor (ambient) air and indoor air, Riaf is the thermal resistance of the inside air film (0.68), and $\Delta Tiaf$ is the temperature differential from inside surface to indoor air.

Temperature data for March 7 at 7AM were used for this calculation. According to the National Weather Service web site, the minimum outside air temperature was 53 °F at 7AM that morning (2). At the same time, the inside surface temperature was 72.4 and the indoor air temperature was 73.2. Using these input values, the total R-value of the wall assembly was found to be R-17.

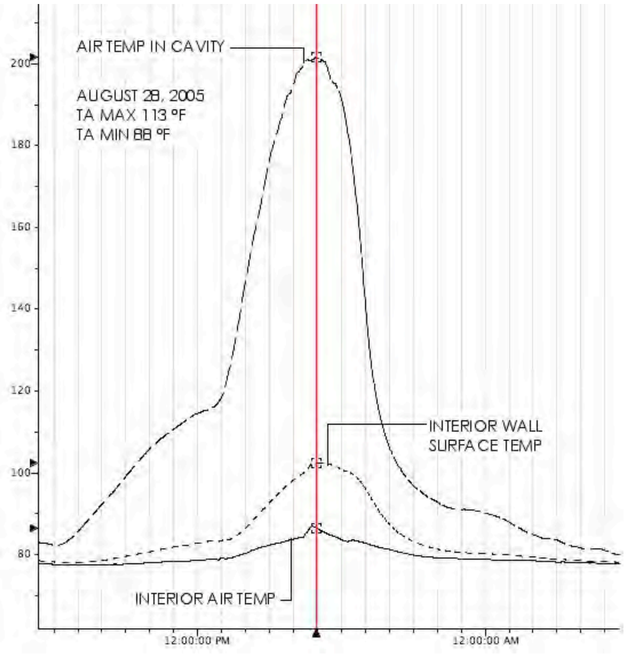

Fig. 4: Temperature and relative humidity data for August 28th, 2005.

The first part of the experiment provided data on the temperature difference between the inside surface of the dry wall and the center of the cavity of the shadow box. Data from a hot day towards the end of August 2005 was plotted with the HOBOware™ program, see Fig. 4.

The air temperature in the cavity reached 201.5 degrees F on August 28th at 5PM, approximately 100 degrees above the interior surface temperature which in turn was recorded at approximately 15 degrees above indoor air temperature. According to the National Weather Service web site, the ambient air temperature reached 113 degrees F that same day, which indicates that the temperature elevation in the cavity peaked at about 90 degrees above ambient. These data show that the opaque portion of the curtain wall sees an elevated outside air temperature - an artificial climate.

With a surface temperature above 100 degrees F, it is safe to assume that the thermal resistance of the inside air film was lower than 0.46, as explained above. With an estimated R-0.44 for the inside air film, the heat flux at this peak condition was calculated as 126 W/m2. The temperature difference between the inside surface and the interior air peaked at 17.556 °F that day. The temperature differential between maximum outside air temperature and concurrent inside air temperature was (113-87)=26 °F. Using a thermal resistance of R-17, the heat flux due to conductance was determined as $Q=\Delta T/R$ is 5 W/m2. This leaves 121 W/m2 to the effect of solar radiation. The Solar Heat Gain Factor SHGF for a west facing vertical surface towards the end of August at 32 degrees NL is around 200 Btu/h-ft2, which translates to 630 W/m2 (3). The SHGC at this peak condition is therefore (121/630)=0.192. This is significantly higher than the assumed SC of 0.03 (similar to an SHGC of 0.034) used for the building energy performance simulations.

Solar radiation data acquisition started on March 2nd. The following days were mostly clear days with no clouds in the sky. Fig. 5 shows the solar radiation data from the Micro Station at the Solar Lab for March 7th superimposed on the temperature data from the HOBO data logger at the building. This graph shows how the temperature elevation inside the sealed air cavity corresponds to the increasing values of solar radiation, which in turn may be seen as evidence of the findings above that the heat flux from the exterior to the interior during heat gain conditions can mainly be attributed to solar radiation. The heat flux at the inside surface peaks about one hour after the solar radiation and shadow box air temperature peak.

Heat flux data from the HFT were recorded manually on March 7th using a Radio Shack Multi-meter. Values were recorded at one hour intervals starting at 8:40 AM and with 15 minute intervals starting at 1:30 PM. The mV (milli-volt) readings were multiplied with 23 (the calibration constant) to get Btu/h-ft2 and then again multiplied by 3.155 to get W/m2. The resulting values were plotted manually on to the graph shown in Fig. 5. This was a mostly sunny day with scattered clouds passing.

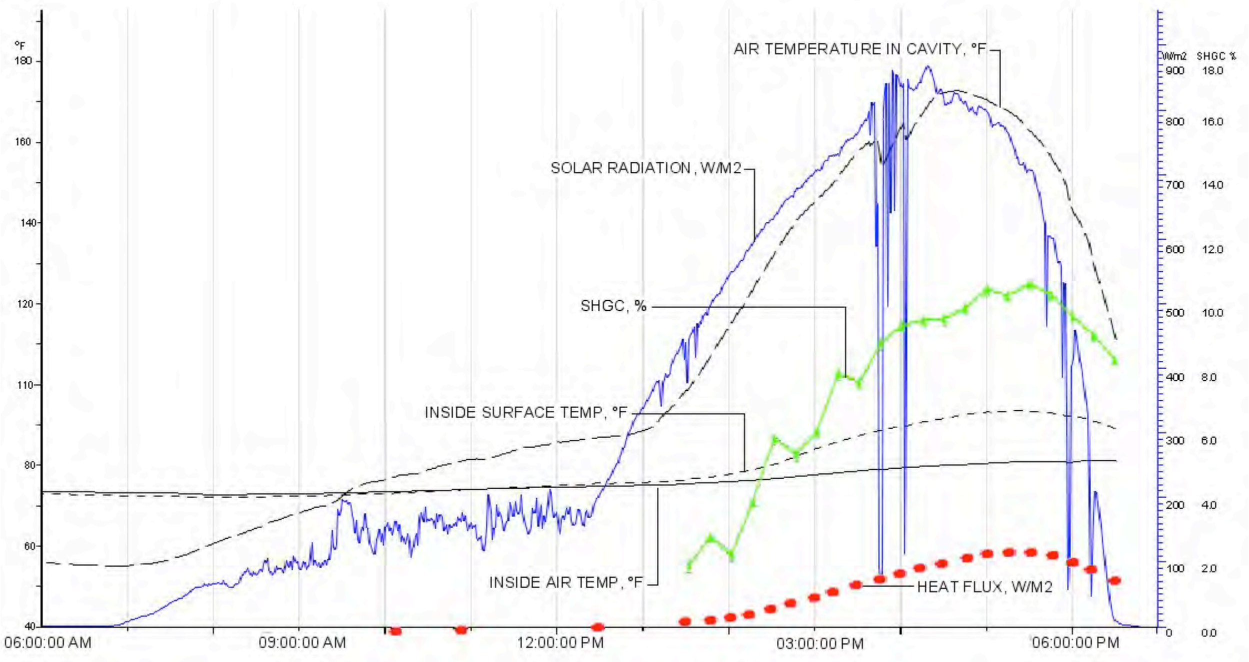

Fig. 5: Solar radiation, temperatures, and heat flux data for March 7, 2006. Graph produced by HOBOware™ v.2 for Mac OSX.

The SHGC was calculated as heat flux divided by solar radiation for each time interval of heat flux data. We used solar radiation data for points in time one hour earlier than the heat flux data to compensate for the observed time lag. The SHGC peaked on March 7th, 2006 at 10.6%. This is more than 3 times the Solar Heat Gain Coefficient of 3.4% used in the building energy performance simulation. We also see how the SHGC increases with increasing temperature in the shadow box. The peak value found on March 7th, 2006 is still well below the estimated SHGC of 19.2% for the hot day of August 28th, 2005.

6. CONCLUSIONS

This experiment is providing data that makes it possible to calibrate the computer simulation of the curtain wall panel as a "window". Analysis of the acquired data shows that the SHGC of the opaque portion of the wall assembly is considerably higher than the SHGC used in the simulation. The data also shows how the SHGC varies with the changing temperature elevation in the cavity (shadow box). This phenomenon may be seen as a dynamic solar heat gain coefficient. These findings have implications on two levels:

1) Ideally, simulation software should recognize a dynamic SHGC. A dynamic SHGC could be tied in with the simulated temperature elevation in the shadow box. To the knowledge of the author, current energy performance

simulation programs do not have the ability to account for a variable, dynamic Solar Heat Gain Coefficient.

2) Since the actual SHGC determined through this experiment is significantly higher than the value used in the building energy performance simulations, these simulations should be performed again with the new values for SHGC. An alternate simulation run could then be used to test the validity of the claim that the building meets ASHRAE 90.1 standards. As it stands now, the results found here indicate that the claim presented by the builder might well be loosely founded.

7. SIGNIFICANCE

Experimental data from this research supports the hypothesis that a wall assembly of the kind examined here has a higher SHGC than anticipated during the design phase. This SHGC is not static, as it fluctuates with the changing temperature elevation in the air cavity of the shadow box. It is essential to the building owner, as well as the scientific community and the design community to fully understand how a wall assembly of this type performs in a hot and dry climate. This research has produced some very important answers.

8. ACKNOWLEDGMENTS

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7. REFERENCES

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