Measuring Dynamic Thermal Resistance of Building Envelope Assemblies

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Abstract:

Thermal resistance of complex building assemblies is presently evaluated through simulation models using vendor published R-values of the various building components. Calculated R-values seldom take into account variations in construction, deterioration of assembly components over time and assemblies consisting of multiple components such as window frames, studs, fasteners, inconsistent insulation, deficiencies in the installation, variable air gaps and thermal bridging. The Building Envelope and Technology Access Centre (BETAC) and SMT Research have installed a large network of sensors embedded throughout the new Skilled Trades and Technology Centre (STTC) located on the Red River College, Notre Dame Campus in Winnipeg, as well as a 32-storey high-rise building located at 360 Main Street in downtown Winnipeg, Manitoba. Several different exterior assembly types have been instrumented throughout the building envelope, as well as the roof and green roof assemblies. The sensor set installed throughout the building consists of heat flux sensors embedded inside specific assemblies alongside temperature sensors positioned across the insulation material. The Dynamic Thermal Reistance can be calculated from the installed sensors and compared to simulated models in order to validate both the monitoring methodology as well as the accuracy of the simulation. The analysis will be performed in real-time during normal building occupancy of the building influenced by the temperature extremes inherent to Winnipeg. Results will be compared and analyzed with respect to external climatic influences as well as an analysis of convective air currents within the wall cavities. This paper will demonstrate the methodology and sensor set required to obtain the required quantitative data in both instrumented buildings. Monitored results from the downtown building will be analyzed and compared against calculated values and model simulations.

Keywords:
Dynamic Thermal Resistance (DTR), Heat Flux, Effective R-value, Monitoring, Modelling, Sensor, Living-lab, Temperature extremes

1. Introduction

This paper covers the methodology and sensor instrumentation required to measure and analyze the Dynamic Thermal Resistance (DTR) of a building. This study addresses two different buildings located in Winnipeg, MB. Both buildings are subjected to a wide range of environmental conditions; seasonal temperature fluctuations from -40ºC to +40ºC, wind gusts in excess of 100 km/h, torrential rain events and winter blizzard conditions make this geographic location ideal for thermal analysis and performance testing.

The STTC building is a 9300m^2 (100,00ft^2) new construction, two-storey multi-purpose educational building used as laboratory and shop space. It will serve as the educational facility used to train and educate students enrolled in RRC's Construction Trades Programs. The building will also serve as an educational tool to all faculty members, providing real time, accessible data from its network of embedded sensors. Seven different exterior wall types are instrumented including six varying opaque wall assemblies and one curtain wall. Also instrumented, are the two varying roof types, including the green-roof assembly. The sensor installation is complete, however the building is not in a controlled state as it is still presently under construction. Once occupied, the building will serve as a '*living lab*' where the data and analysis will be discussed in future papers.

The existing 32-storey high-rise, 56,000m^2 (600,000ft^2) office building located at 360 Main Street in downtown Winnipeg underwent a major renovation with a complete replacement of its exterior wall façade with a new spandrel panel system. Sensors were embedded in the new façade on one floor and several months of data is presented and discussed in this paper.

In late 2013, Manitoba adopted The National Energy Code for Buildings (NECB) and began enforcement in December 2014. The NECB sets the minimum acceptable standards for building performance of new construction and those undergoing major renovations, as related to energy use. Part 3-*Building Envelope* of NECB 2015 details the minimum thermal transmittance characteristics of building envelope assemblies. Achieving targets is accomplished by following one of three Compliance Path methods. (National Energy Code for Buildings, 2015).

1. The Prescriptive Path stipulates a building component or assembly type to be built to a certain minimum R or U-Value.
2. The Trade-Off Path allows for an assembly type or component of lower R-Value to be used when a similar, corresponding assembly type or component has a higher R-Value, all whilst

maintaining the minimum prescriptive performance levels.

3. The Performance Path requires the proposed building be modeled using specified computer software, and shows the proposed design of the building performs better than that of a similar referenced building.

All three Compliance Paths and modeled methods require calculations and inputs such as the building geometry, size, as well as knowledge of specific building components with known R-values. All methods take into account varying aspects of the thermal bridging occurring through the assemblies, however, they do not take into account the variations in construction, inconsistent insulation and materials, variable air gaps or the deterioration of assembly components over time (Modera, M. P., Sherman, M. H., and Sonderegger, R. C.,1985). The major contribution of this study is to design a system capable of measuring heat flux over a large surface area in order to encompass a variable complex assembly. The heat flux in conjunction with the change in temperature across the assembly provides the in-situ effective R-value or *Dynamic Thermal Resistance* of the wall assembly.

The impact of this study is to establish a quantitative metric to benchmark the energy efficiency of pre-existing assemblies and materials. This will allow unique materials, assemblies and construction techniques to produce a quantitative measurement that can be recorded and monitored. Energy savings will be achieved by maintaining optimal thermal efficiency over time as the monitored wall structures will essentially be subject to continuous real-time commissioning.

2. Sensor Installation Plan - RRC STTC

Installed throughout the building, on seven different exterior wall types and roofing assemblies, are a network of moisture and thermal sensors.

Figure 1. Red River College's Skilled Trade and Technology Centre (Photo Credit RRC)

Green Roof Performance Monitoring

Moisture Detection Sensors are installed in a dense 1.5m (5ft) grid pattern within the green roof assembly. In addition to moisture detection sensors located under the roofing membrane itself, the thermal resistance of the roof is instrumented with heat flux sensors on the underside of the roof, along with temperature sensors on both the bottom and top portions of the assembly.

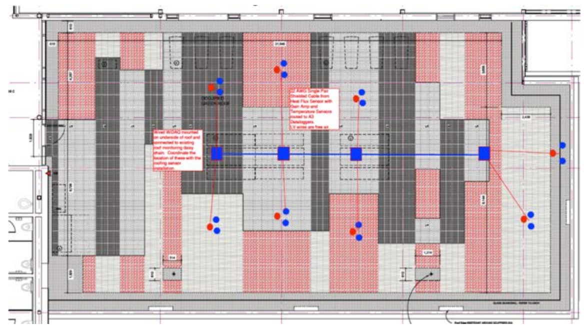


Figure 2. Green roof heat flux and temperature sensor locations.

Building Envelope Sensor Installation

The STTC building has sensors embedded within six different exterior opaque wall types, including variations of masonry and metal siding. Also instrumented are vision walls, including windows and the curtain wall assembly. The type of sensor and placement is dependent on the wall, elevation type and mounting assembly. Moisture Detection Sensor (MDS) tape was placed in areas susceptible to moisture intrusion. Point Moisture Monitoring (PMM) sensors were placed in the plywood mounts for the curtain walls, and a combination of heat flux and temperature sensors were placed around the specific assemblies and insulation types to measure thermal efficiency and thermal resistance. A typical sensor installation with temperature, heat flux and differential pressure is shown in Figure 3 and Figure 4. Differential pressure sensors were installed to observe the airflow magnitude and direction across the various building envelope assemblies.

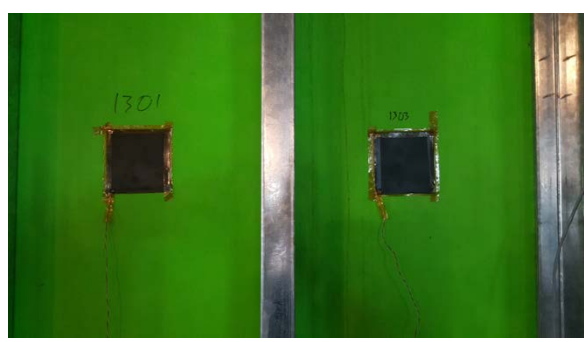


Figure 3. Interior Heat Flux Sensor Installation

Figure 4. External Heat Flux, Temperature and Pressure Installation

3. Sensor Installation Plan – 360 Main Street

Heat flux and temperature sensors were installed on the 13th floor of the 32-storey building located in Winnipeg's downtown. The building has 12 different wall facings; however, six varying orientations were selected to be instrumented, to provide a representative sample of the buildings perimeter.

Figure 5. 32-Storey High-Rise Building

Sensors were positioned at the ceiling level to avoid the space heating equipment, as the heaters would have an influence on the heat flux sensor readings. In addition, the location allows the data loggers to be connected without any wires or cables to be visible within the space. The sensor location layout is shown in Figure 6.

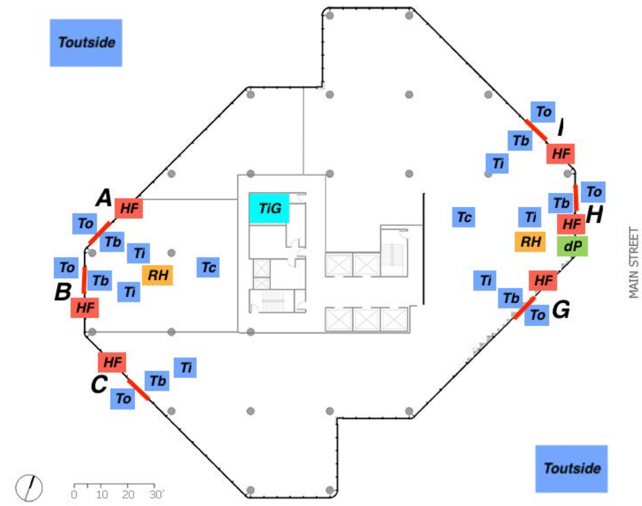


Figure 6. Sensor Locations

Identification Labels	
To	Temperature outside of back pan insulation
Tb	Temperature located on inside of back pan
Ti	Temperature 10 cm away from back pan inside airspace
Tc	Ambient room temperature
HF	Heat Flux Sensor
RH	Relative Humidity sensor located in A3
dP	Differential Pressure
TiG	Wireless Gateway
Toutside	Outdoor temperature from a local weather station was used.

Sensors installed around the spandrel panel of the curtain wall assembly are shown in Figure **7**. Temperature sensors are installed between the back pan and exterior curtain wall (To) as well as on the interior back pan (Tb) and 10cm (4 inches) off the interior back pan (Ti). The exterior ambient temperature (Toutside) and the the interior room temperature (Tc) are used to calculate the temperature across the entire assembly. The Dynamic Thermal Resistance is calculated using the external temperature (Toutside) and the interior ambient temperature (Tc). The heat flux is measured using a PHFS-09e FluxTeq heat flux sensor as shown in Figure 8.

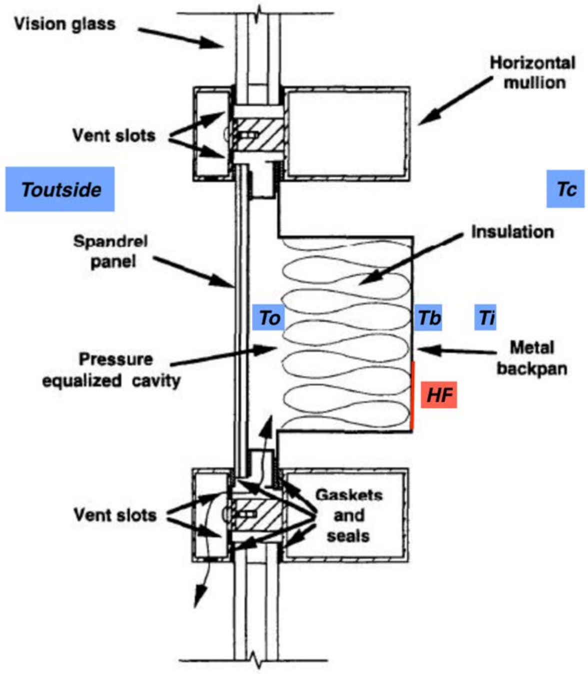


Figure 7. Sensors across back pan

Dynamic Thermal Resistance (DTR) is calculated using the standard R-value formula. Results are expressed in R-value (US) units.

$$RSI = \frac{\Delta T}{Heat\ Flux} = \frac{T_{outside} - T_{inside}}{W/m^2}$$

$$DTR = RSI \times 5.678263337$$

The locations of the sensors on the materials are shown in Figure 8 and Figure 9. Tc was used as the internal sensor to avoid any back pan radiant temperatures.

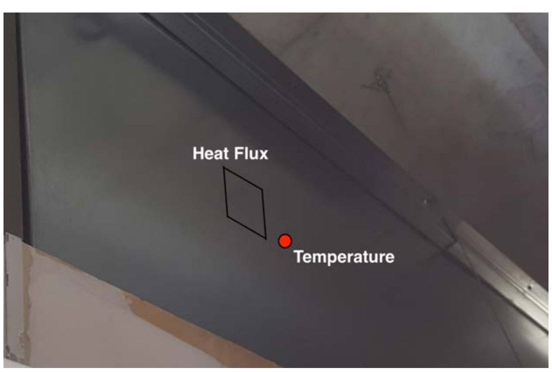


Figure 8. Internal Temperature (Ti) sensor location

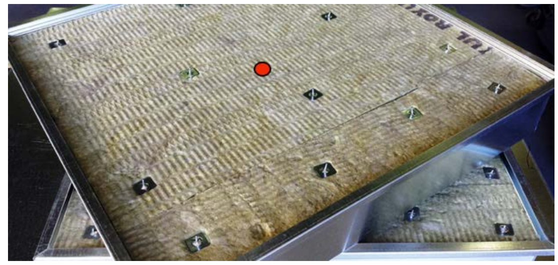


Figure 9. External temperature (To) sensor location

- The external back (To) sensor was installed on the external side of the insulation by drilling a small hole in the back pan. The back pan holes were sealed using the sealant used onsite and the hole was covered with a self- adhered membrane.
- The sensor is flush with the insulation and did not come in contact with the spandrel panel. A stopper was fastened to the sensor so that it cannot in anyway be extended too far and touch the panel.
- Wiring and thermistors were engineered to handle temperatures up to +100ºC.
- This configuration will give the R value across the back pan but not the window. This is compliant with NBC A-9.36.2.4.(2) D – Note 5 that states “materials installed towards the exterior of a vented air space cannot be included in the calculation of effective thermal resistance of the assembly. (NBC A-9.36.2.4.(2) D – Note 5, 2015).

The Heat Flux sensor is connected to a 1000 times instrumentation gain amplifier then connected to a 24-bit high precision data logger A3 4R4V unit. *To* is installed through the back pan as shown in Figure 9 and is located behind the self- adhered membrane. *Tb* is taped with foil tape to the back pan and *Ti* is extended 4cm off the back pan. All wires are routed to the A3 data logger.

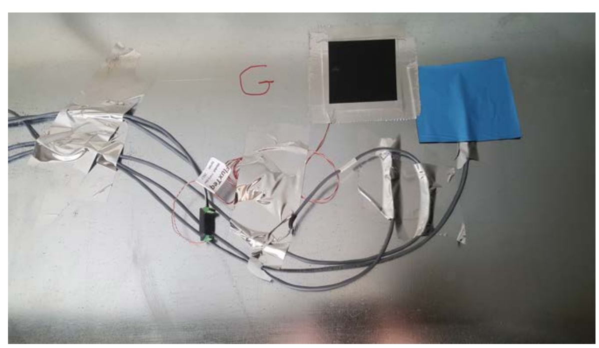


Figure 10. Typical sensor installation

The A3 8R and A3 4R4V units are both mounted at the central wall related to the adjacent sensor installation locations. These units are secured using Velcro to the back pan for easy removal. No further penetrations were made in the back pan to mount equipment.

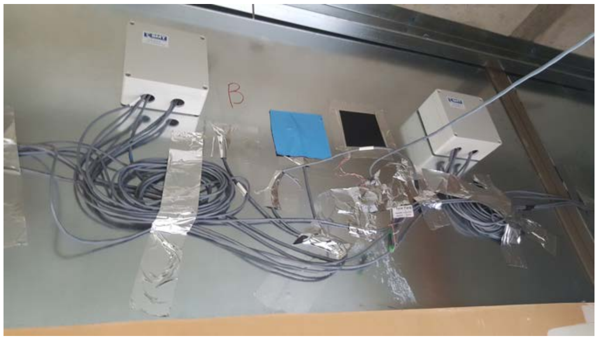


Figure 11. Typical data logger and sensor installation

4. Pressure Differential Sensor Installation

One differential pressure sensor was be installed between the Pressure equalized cavity (P2) and the interior airspace P1. This was done by placing a pressure tap through the assembly in similar fashion to the temperature sensors. The differential pressure is reported as ∆P = P2 – P1. A positive pressure will mean that air is passing into the building and a negative pressure will represent air moving from the inside to outside. An attempt will be made to further enhance the pressure data acquisition by providing a tap to the exterior of the spandrel panel, P3. This valuable information will assist to further understand the pressure differentials across the assembly, see Figure **12**.

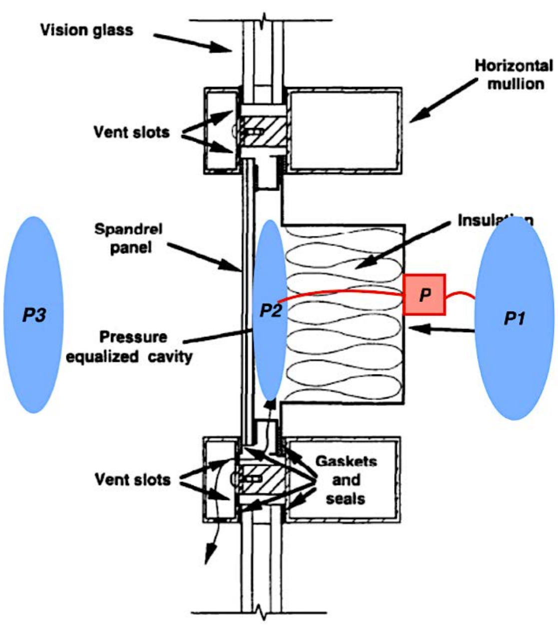


Figure 12. Differential Pressure Installation

A pressure hose connected to a differential pressure sensor is installed from the outer insulation behind the spandrel panel and the other hose of the sensor is located in the interior airspace.

Figure 13. Differential pressure sensor installation

5. Weather Station

The weather station within the closest proximity is located at the University of Winnipeg as shown in Figure 14. This weather station has been attached to the Analytics profile so that weather data can be graphed alongside the other sensor data. In order to get more accurate results a weather station added to the roof of the building will be investigated as well as external temperature sensors on the 4 different wall facings of the building.

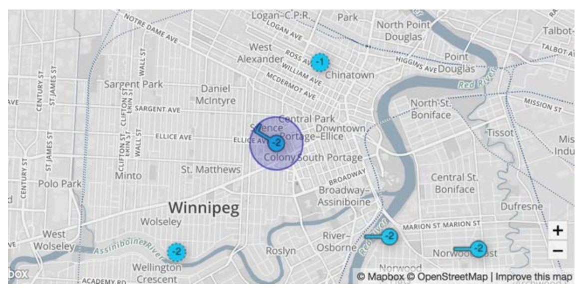
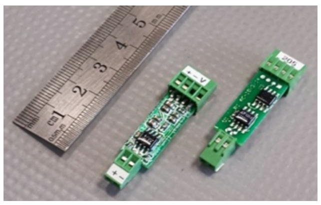


Figure 14. Weather station location

6. Data Acquisition Hardware

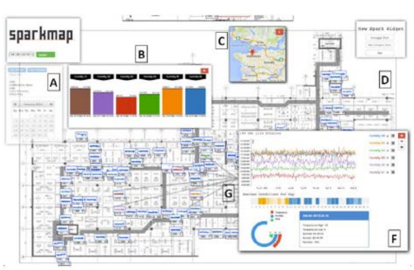
Sensors are routed to the data acquisition hardware that performs the analog to digital conversion. The sensors transmit their digital data wirelessly to a gateway located in a network room on the same floor. This gateway periodically synchronizes data with a cloud based network server where the data is archived for further analysis. Conversions and compound/virtual sensor sets are calculated on the network server and are available for graphing and further analysis using tools provided by the Analytics engine.



Sensors – Temperature, Heat Flux and Pressure
↓

Data Acquisition and Analog to Digital Conversion
↓

Gateway Synchronizes data with the Network Server
↓



Analytics allows post processing, sensor comparisons and facilitates calculating new sensors based on multiple sensor inputs

7. Sensors

Heat Flux (HF)
The FluxTeq PHFS-09e heat flux sensor was designed to cover large compound areas so the heat flow of the insulation material and surrounding materials can be recorded. The Heat Flux sensors are connected to a instrumentation gain amplifier with 1000 times gain and then connected to a high resolution data acquisition unit

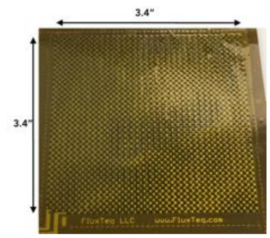


Figure 15. Heat Flux Sensor (without covering)

Temperature (T)
Epoxy Thermistor beads are used for temperature sensing.

Figure 16. Thermistor

Differential Pressure Sensors (DP)
Differential pressure sensors are integrated with the A3 Data Logger with an auto zero feature where the sensor will zero itself every 24 hours in order to negate any long-term drift of the pressure data being collected.

The sensor used is a 0.25” H_2O sensor or ± 62 Pa sensor made by AllSensors.

Figure 17. Differential Pressure Sensor

8. Results: 360 Main Street

The sensor installation at the RRC Skilled Trade and Technology Centre is complete however consistent data is presently unavailable, thus results for 360 Main Street will be presented and discussed at this time.

Data collection started on September 2017 and continues. Temperature data for this period is shown in Figure 18 on the East side and Figure 19 on the West side. Temperatures as high as 100ºC were observed in the cavity between the back pan and glass. The boxed areas shown in Figure 18 are the areas explained further in Figure 20 to Figure 23.

Temperature

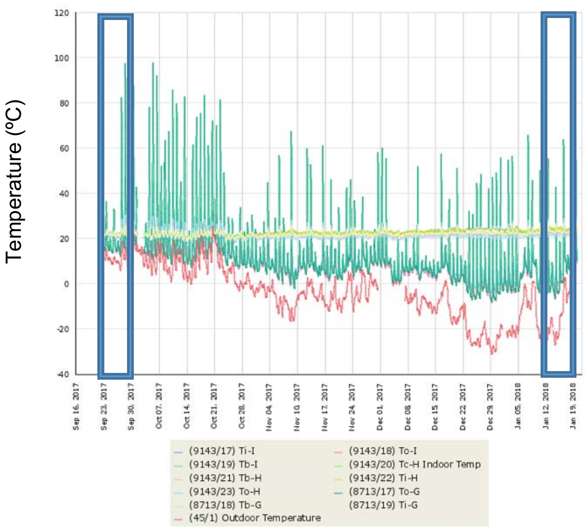


Figure 18. Temperature East

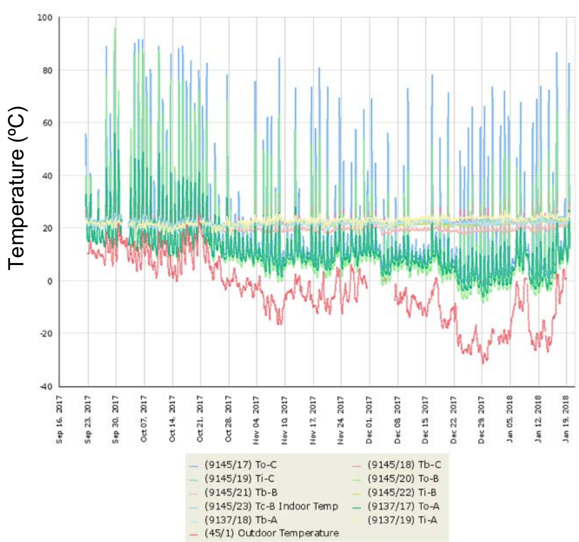


Figure 19. Temperature West

Dynamic Thermal Resistance

Outdoor and indoor temperatures as well as the heat flux and dynamic thermal resistance located on the East side are shown in Figure 20. A relatively warm week in September is shown.

During the transition of heat flow from negative to positive, the DTR experiences an off the scale reading due to a zero crossing instance, these are the out of range readings seen in the graphs.

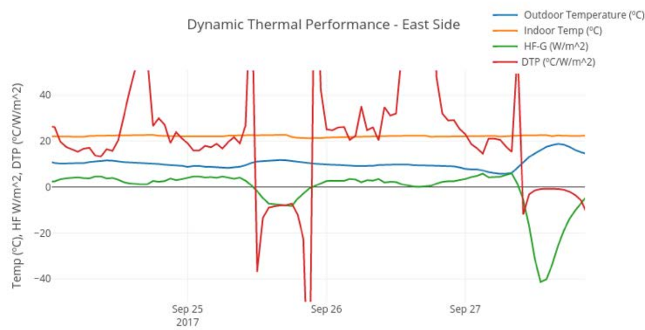


Figure 20. Dynamic Thermal Resistance – East September 2017 – warm week

At night, when the solar loading is minimized, an average DTR of ~15 ºC/W/m^2 is recorded indicating a thermal transfer from the warmer interior of the building to the cooler exterior of the building. During the day a DTR of ~-10 ºC/W/m^{2}is briefly recorded indicating a thermal transfer from the warmer exterior to cooler interior.

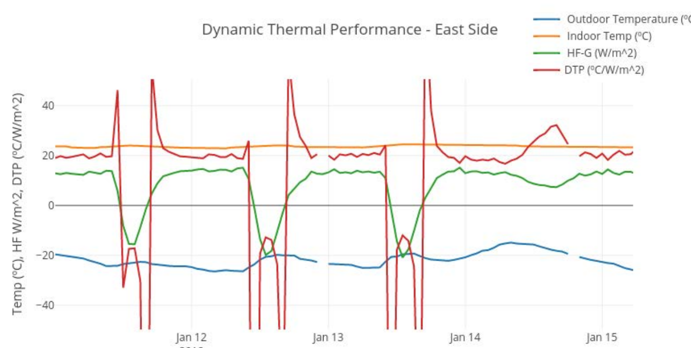


Figure 21. Dynamic Thermal Resistance – East January 2018 – cold week

Outdoor and indoor temperatures as well as the heat flux and dynamic thermal resistance located on the East are shown in Figure 21. A typical cold week during January is shown. During the winter months we see a DTR of 20 ºC/W/m^2. The solar loading during the day continues to cause a thermal transfer from outside to inside of -10 ºC/W/m^2

A similar trend was observed on the West side of the building as shown in Figure 22 and Figure 23.

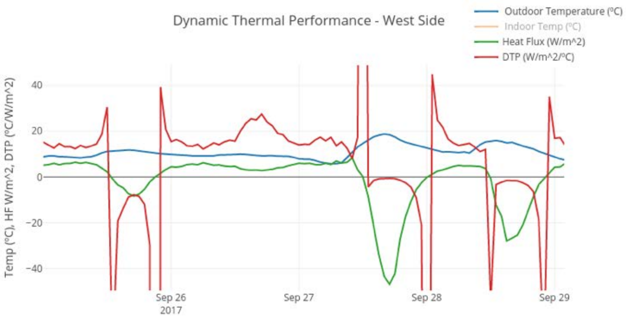


Figure 22. Dynamic Thermal Resistance – West September 2017 – warm week

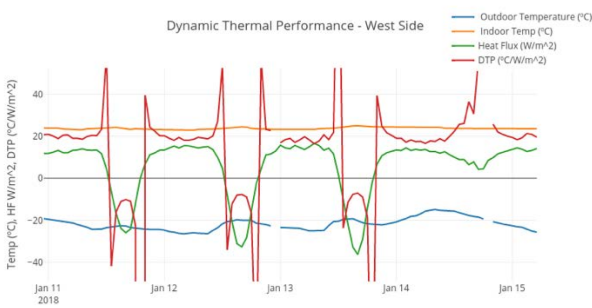


Figure 23. Dynamic Thermal Resistance – West January 2018 – cold week

Differential Pressure

The differential pressure sensor location at location H is situated from the building interior to the cavity between the back pan insulation and external façade. The differential pressure oscillated between -5 Pa and 85 Pa. The pressure sensor has a range of ±62 Pa. The range between 62 Pa and 85 Pa is considered to be maxed values.

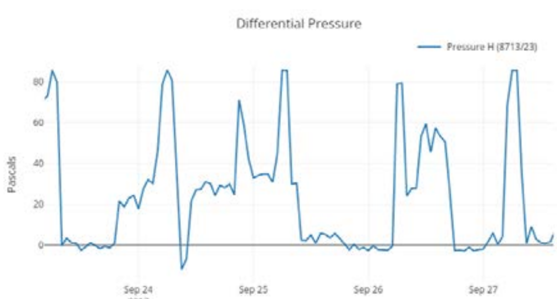


Figure 24. Differential Pressure - September 2017

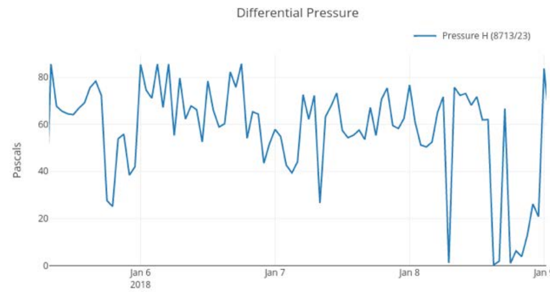


Figure 25. Differential Pressure January 2018

9. Conclusions and Outlook

The sensor network installed in the Red River College STTC building will be producing consistent data in early 2018. As a result an analysis cannot be compiled during the publish date of this paper.

An analysis of the back pan insulation installed at 360 Main Street, shows a Dynamic Thermal Resistance value during a stable range in the 8 ºC/W/m^2 range. The spikes in the DTR value are a result of the large temperature swings that occur due to solar radiation. Temperatures in the order of 100ºC were observed in the summer, and temperatures in the 50ºC range were observed in the winter, when outdoor temperatures were in the -25ºC range.

The instrumented floor is used for staging the swing stages used to repair the other floors of the building. As a result, the interior temperature and pressure stabilization may not reflect the normal operation conditions of the building. Monitoring of the building will continue during normal occupancy of the building.

The preliminary findings obtained in this paper suggest significant variations between the computer modelled effective thermal resistance assumed in the design versus the actual Dynamic Thermal Resistance for the building envelope. Further research is required to develop a relationship based on additional data which will more accurately predicts the Dynamic Thermal Resistance for the building envelope at the design stage.

Acknowledgements

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We gratefully acknowledge Marwest Construction and ARTIS REIT for permission to install sensors as well as the financial support to instrument 360 Main Street.

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