Evaluation of the thermal performance of innovative pre-fabricated wall systems through field testing

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ABSTRACT

The thermal performance of two innovative pre-fabricated wood-frame wall systems was evaluated in comparison with a conventional 2x6 wood frame wall through one year's field monitoring on BCIT's Building Envelope Test Facility. Prefabricated wall system I has 4" Expanded Polystyrene (EPS) infill in the stud cavity with 1" additional EPS added on the interior side of 2x4 wood stud. Prefabricated wall system II has 4" EPS infill in the stud cavity only. The conventional 2x6 wood frame wall has 5-1/2" fiberglass insulation infill in the stud cavity. The effective thermal efficiency of these test walls is evaluated in terms of heat flux, effective in-situ R-values, and temperature distribution.

The heat flux measurements show that, in comparison with the conventional 2x6 wood frame wall, prefabricated wall system I with 4" EPS infill in the stud cavity has 5.1% less heat loss and 16% less heat gain and the prefabricated wall system II with 1" extra EPS has 22.9% less heat loss and 37.5% less heat gain. The improvement of thermal efficiency in the prefabricated wall systems is mainly attributed to the significant improvement over the stud areas. Estimated effective R-values over the winter months from December 2008 to March 2009 show that the R-value over the stud area in prefabricated wall system I is improved by 32.7% while the R-value over the cavity area is reduced by 8.7%, resulting in a net improvement of effective wall R-value by 2.9%; and the R-value over the stud area in prefabricated wall system II is improved by 112.3% with only a 2.6% improvement in the R-value over the cavity area, resulting in a net improvement of effective wall R-value by 26.5%.

Temperature measurements show that the interior surface temperatures over the stud area in the conventional wall fluctuate much more and are higher during the summer months and lower during the winter months compared to the prefabricated systems, due to the thermal bridging effect of the stud.

INTRODUCTION

Prefabricated wood-frame wall systems provide many advantages such as better controlled workmanship, air tightness, and detailing. The recent British Columbia Building Code (BCBC, 2006) change in the requirement of R20 wall insulation raised the question whether a pre-fabricated wood-frame wall system with one layer 4" Expanded Polystyrene (EPS) insulation would provide a comparable thermal performance as a conventional 2x6 wood frame wall with 5-1/2" fiberglass batt insulation. Although the nominal R-value of 5-1/2" fiberglass insulation is higher than one layer of 4" EPS, the overall effective thermal resistance of the wall assembly is significantly influenced by the on-site workmanship. In this study, the thermal efficiency of two prefabricated wall systems, system I (PCI) with 4” EPS infill in the stud cavity with 1” additional EPS added on the interior side of the 2x4 wood stud and system II (PCII) with 4” EPS infill in the stud cavity only, was evaluated in comparison to a conventional 2x6 wood frame fiberglass walls using the Building Envelope Test Facility at BCIT. This test includes monitoring the thermal and moisture performance of three 4' by 8' test walls over one year’s period under controlled indoor and real climatic outdoor conditions. This paper presents the experimental setup and result analysis of the thermal performance in term of heat flux, effective thermal resistance, and temperature measurements.

EXPERIMENTAL SETUP

Test facility

The experimental study was carried out at BCIT Building Envelope Test Facility (BETF) (Figure 1). The research facility is designed to evaluate the hygrothermal performance of full-scale building envelope assemblies under simulated indoor and real climatic outdoor conditions. The 44' x 28' two-story structure can accommodate in total sixty-two 4' x 8' (1.2 m by 2.4 m) panels. The panels are removable, allowing for ease of implementation of any type or location of testing required. Two mechanical systems are fitted within the facility allowing the separation of interior spaces into two conditioned horizontal zones, thus allowing control of the indoor boundary conditions, namely, temperature and relative humidity, at the desired values. Each system can maintain indoor temperature within the range of 18–26ºC, with a precision of ±2ºC, and relative humidity within the range of 40–80%, with a precision of ±5%. The facility is equipped with a data acquisition system with over 600 channels, allowing for the monitoring of hygrothermal conditions within wall assemblies including temperature, relative humidity, moisture content, heat flux, air velocity, wind-induced pressure, and incidence of condensation and rain penetration. The facility is also equipped with a weather station mounted on the rooftop of the facility to measure the outdoor boundary conditions including wind speed, wind direction, solar radiation on both horizontal and vertical surfaces, and horizontal rainfall. Driving rain on wall surfaces is also collected. More information about this facility can be found in (Ge, et al., 2008).

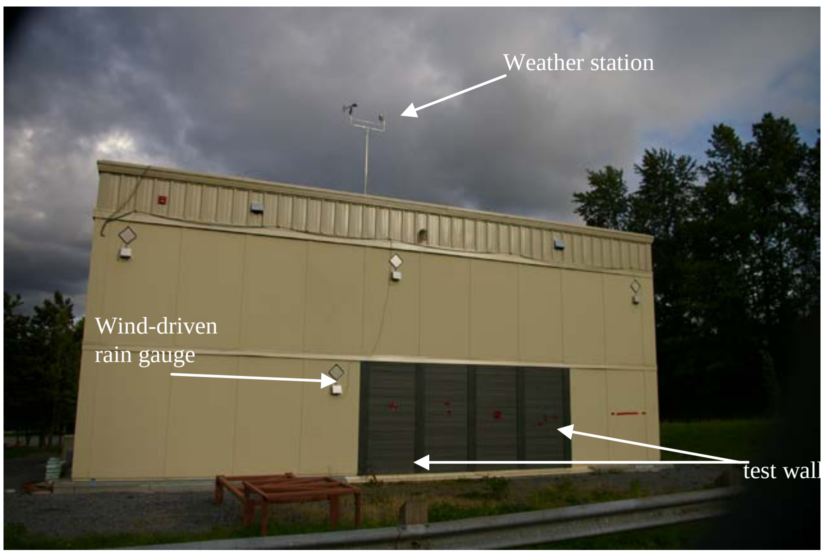


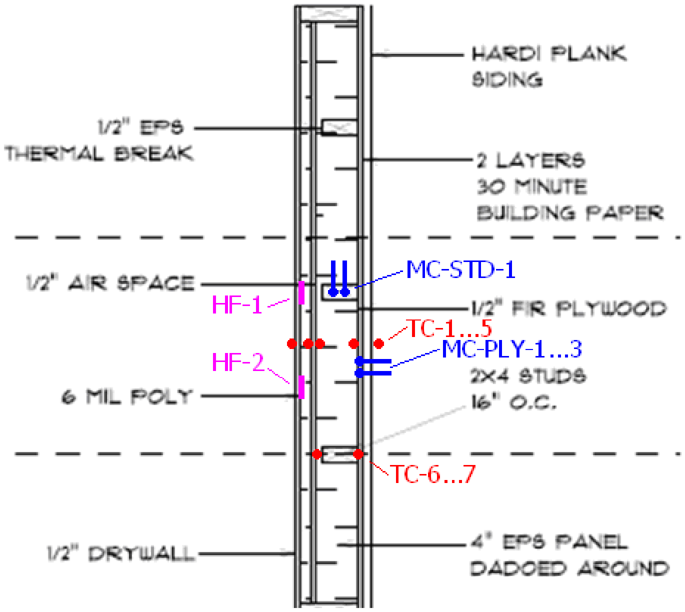
Figure 1. BCIT’s Building Envelope Test Facility (Northwest view).

Test panels and instrumentation

Three 4' x 8' test panels, PCI, PCII, and conventional system, were fabricated in a manufacturing plant and installed in the Northwest section of the BETF. The configuration of these walls along with corresponding sensors installed to measure heat flux, temperature, and moisture content are shown in Figure 2. Prefabricated system I, named PCI, has 4” EPS infill in the 2x4 wood stud cavity with an extra 1” EPS in the air gap between the 4” EPS insulation and the gypsum drywall. Prefabricated system II, named PCII, has 4” EPS infill in the wood stud and 1-1/2" air gap between the 4” EPS insulation and the gypsum drywall. The end studs of the prefabricated wall systems are 2x6. The conventional 2x6 wood frame wall, named CON, has 5-1/2” fiberglass insulation in the 2x6 wood stud cavity.

The cores of the test walls including framing, insulation, polyethylene sheet, and plywood sheathing were fabricated and instrumented in a controlled environment, therefore, a good workmanship in fabricating the conventional wall was achieved. The building paper as sheathing membrane, fiber cement plank siding, and gypsum drywall were installed after the walls were in place at the test facility. To provide the thermal and moisture separation from the surrounding existing walls, the polyethylene sheet was wrapped around the edge of the stud to overlap with the building paper. The 2" gap between each test wall was fitted with rigid insulation and sealed to the side with sealant and foam backer rod.

The central bay of each test wall, made up of two 2x4 wood studs at 16" spacing for prefabricated wall systems and two 2x6 wood studs at 16" spacing for the conventional wall, was instrumented and the other two 16" bays are used as guard bays. The parameters monitored include temperature, moisture content, and heat flux across the test walls. In total, 35 thermocouples, 12 pairs of moisture pins, and 7 heat flux transducers were installed in the walls. The details about moisture content measurements and results will be presented in a subsequent paper. The temperature profiles across both the insulation and stud areas were monitored. Two additional thermocouples were installed on the interior surface of the cavity insulation, one at the bottom and the other at the top to monitor the stratification effect that may exist within the air gap. The heat fluxes through both the insulation and stud areas were measured in each wall. For PCII, an additional heat flux sensor was also installed on the exterior surface of the gypsum drywall over the insulation area. The layout of the sensors in each wall is shown in Figure 2. Thirty-gauge premier grade type T (copper and constantan) thermocouple wires were used to measure temperature. They were calibrated using an isothermal bath (accuracy ±0.01^{o}C) with an Agilent Switch Unit (model 34970A) at three different temperatures, 10^{o}C, 20^{o}C, and 30^{o}C. The system measurement accuracy is ±0.5^{o}C. Since the heat flux sensors were purchased specifically for the study, the factory-calibrated coefficients are used and verified by heat flow meter measurements.

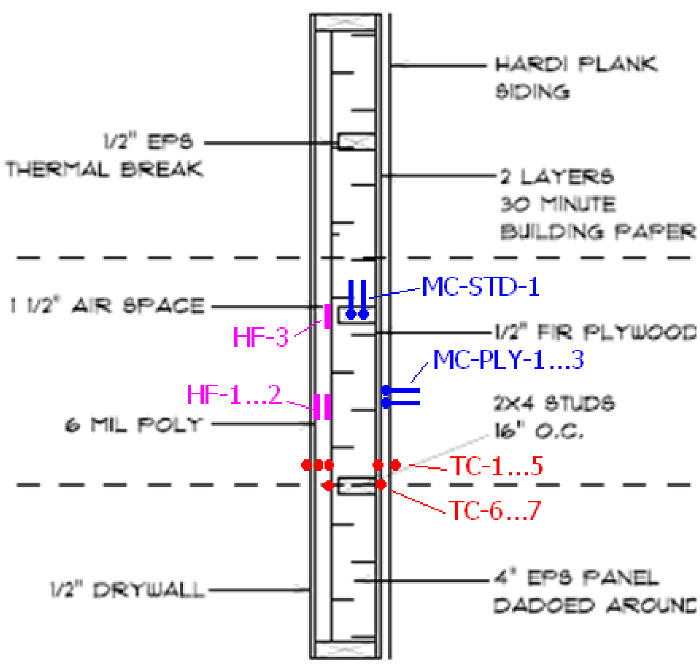


From exterior to interior:

- horizontal shiplap fiber cement siding
- two layers 30-minutes asphalt-impregnated building paper
- 12.5mm plywood sheathing board
- 4" expanded polystyrene insulation
- ½" air gap
- 1" expanded polystyrene insulation
- 6-mil polyethylene sheet
- 12.5mm gypsum board

Figure 2a. Configuration and sensor layout in prefabricated wall system I, PCI.

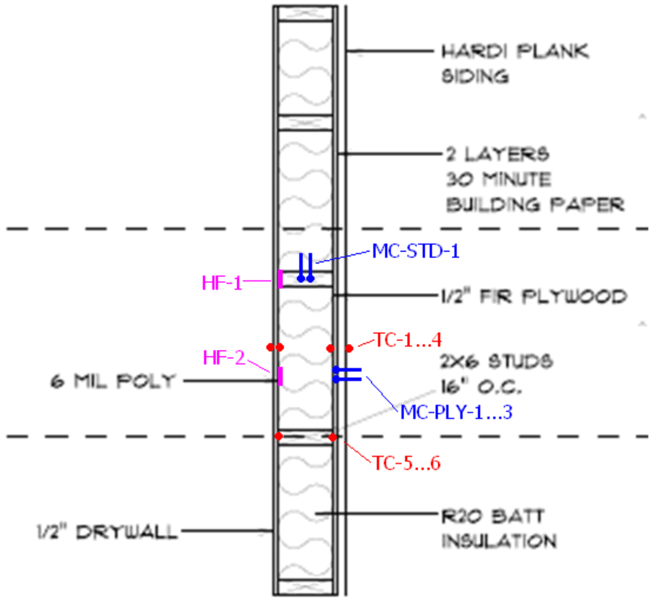
*Note: TC-Thermocouples, HF-heat flux sensor, MC-moisture content pins.



From exterior to interior:

- horizontal shiplap fiber cement siding
- two layers 30-minutes asphalt-impregnated building papers
- 12.5mm plywood sheathing board
- 4" expanded polystyrene insulation
- 1½" air gap
- 6-mil polyethylene sheet
- 12.5mm gypsum board

Figure 2b. Configuration and sensor layout in prefabricated wall system I, PCII.



From exterior to interior:

- horizontal shiplap fiber cement siding
- two layers 30-minutes asphalt-impregnated building paper
- 12.5mm plywood sheathing board
- 138 mm fiber glass insulation
- 6-mil polyethylene sheet
- 12.5mm gypsum board

Figure 2c. Configuration and sensor layout in the conventional wall 3, CON.

The test panels are exposed to Vancouver weather conditions on the exterior and controlled indoor temperature and relative humidity conditions on their interior surfaces. The local outdoor climatic conditions including temperature, relative humidity, wind speed and direction, global solar radiation, and horizontal rainfall are measured with a weather station that is mounted on the rooftop of the BETF. The indoor temperature and relative humidity conditions are controlled by thermostat and humidistat. The temperature set point is 21°C and was kept constant throughout the monitoring period. The relative humidity was initially set at 50% and changed to 35% during the winter months to avoid excessive moisture condensation inside the test panels, and reset back to 50% after May 2009. Figure 3 shows the monthly average indoor temperature and RH during the test period. The analysis is based on data collected for one year from Sept. 1, 2008 to Aug. 31, 2009.

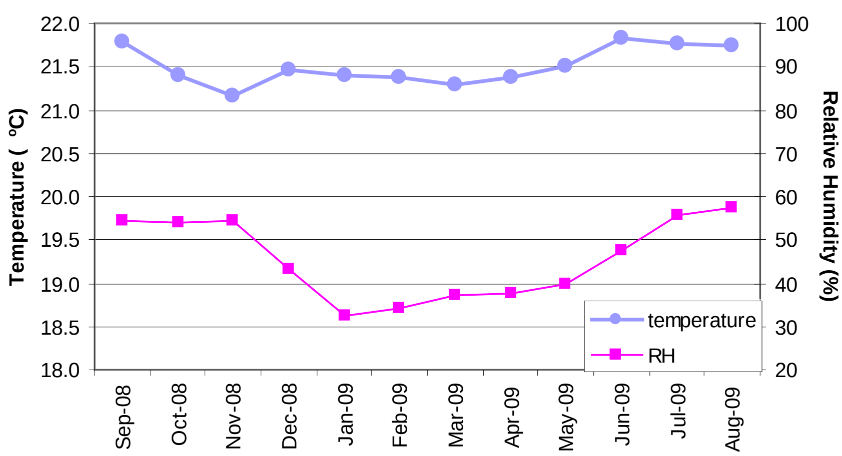


Figure 3. Monthly average indoor temperature and RH over the test period from September 2008 to August 2009.

RESULTS AND ANALYSIS

The thermal performance of the prefabricated test walls are evaluated using the heat flux measured in comparison with the conventional wall system. An effective thermal resistance R-value is also calculated for each wall for the winter months from December 2008 to March 2009 when the heat flux is mainly outward i.e. heat loss. In addition, the thermal efficiency is evaluated by comparing the interior surface temperature of the walls, which has an impact on risks for surface condensation, mold growth, and occupants' thermal comfort.

Heat flux measurements

The heat fluxes through the stud and insulation areas are compared for the three test walls. As shown in Figure 9, the heat fluxes through the stud areas are all negative, meaning heat loss from indoor to outdoor from October 2008 to the beginning of April 2009. From April onward until the end of August 2009 the heat fluxes are two ways, i.e., heat gain during daytime due to higher solar radiation and warmer outdoor temperatures, and heat loss during nights when outdoor air cools down. It is shown in Figure 9 that the PCI system has the lowest heat loss and heat gain through the stud area followed by the PCII system, although the difference between PCII and the conventional wall is more significant during the heating season. The conventional wall system has the highest heat loss and heat gain at the stud area.

The same trend is observed for the insulation area. As shown in Figure 10, the heat fluxes are all negative, meaning heat loss from indoor to outdoor from October 2008 to the beginning of April 2009. From April 2009 until the end of August 2009, the heat fluxes become two ways, i.e., heat gain during the daytime and heat loss during the night. The difference in heat fluxes through the insulation areas among the three test walls is not significant during the heating season, and it only becomes obvious starting from April to the end of August, 2009. As shown in Figure 10, the PCI system has the lowest heat gain during the day and the lowest heat loss during the night from April to August, followed by the PCII system, and the conventional wall system has the highest heat loss and heat gain during this period.

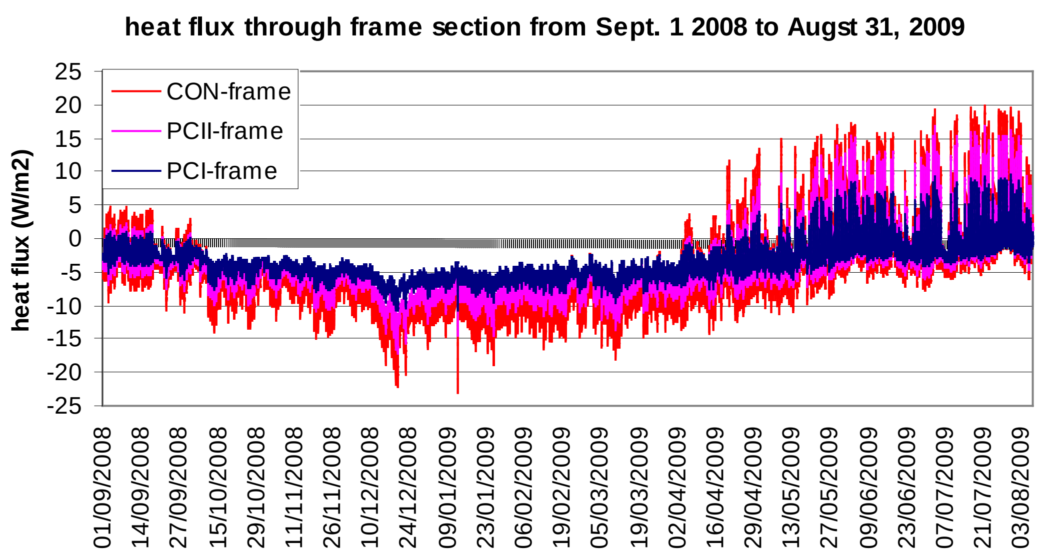


Figure 4. Comparison of heat fluxes through the stud areas among the three test walls over the test period from September 2008 to August 2009.

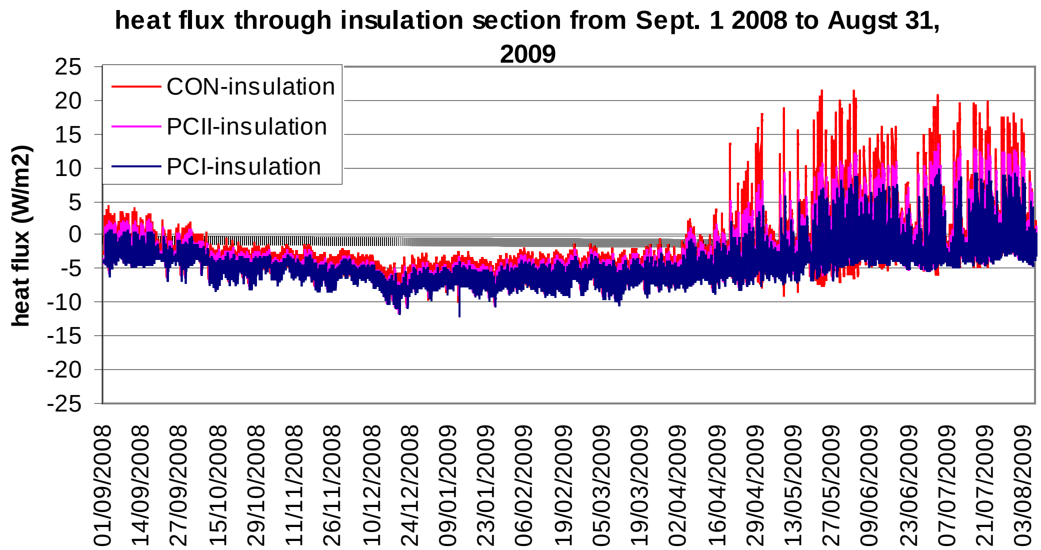


Figure 5. Comparison of heat fluxes through the insulation areas among the three test walls over the test period from September 2008 to August 2009.

The detailed comparison in terms of total heat loss, total heat gain, total heat flow, and average heat flux over stud and insulation areas is listed in Table 1. The readings of the conventional wall are used as the reference. The total heat flow is the sum of the absolute value of both heat loss and heat gain.

Table 1: Total heat loss, total heat gain, total heat flow, and average heat flux in the three test walls over one year's test period.

	stud			Insulation			wall total		
	PCI	**PCII**	**CON**	**PCI**	**PCII**	**CON**	**PCI**	**PCII**	**CON**
total heat loss (MJ/m^2/year)	16.80	26.75	35.30	63.51	72.071	68.86	80.31	98.82	104.15
***deviation from conventional wall (%)**	**-52.4**	**-24.2**		**-7.8**	**4.7**		**-22.9**	**-5.1**	
total heat gain (MJ/m^2/year)	2.64	4.62	6.36	11.50	14.38	16.25	14.13	19.00	22.61
deviation from conventional wall (%)	**-58.6**	**-27.4**		**-29.2**	**-11.5**		**-37.5**	**-16.0**	
total heat flow (MJ/m^2/year)	19.44	31.37	41.66	75.00	86.45	85.10	94.21	117.77	126.76
deviation from conventional wall (%)	**-53.3**	**-24.7**		**-11.9**	**1.6**		**-25.7**	**-7.1**	
Average absolute heat flux (W/m^2)	3.14	5.08	6.74	3.03	3.50	3.44	3.06	3.81	4.10
deviation from conventional wall (%)	**-53.3**	**-24.7**		**-11.9**	**1.6**		**-25.7**	**-7.1**	

*The conventional wall is used as the reference in the deviation calculation.

The total heat loss through the stud area is reduced by 52.4% in PCI and 24.2% in PCII in comparison with the conventional wall; and the total heat loss through the insulation area is reduced by 7.8% in PCI but increased by 4.7% in PCII, resulting in a net reduction of heat loss through the whole wall by 22.9% in PCI and 5.1% in PCII. The total heat gain through the stud area is reduced by 58.6% in PCI and 27.4% in PCII in comparison with the conventional wall; and the total heat gain through the insulation area is reduced by 29.2% in PCI and 11.5% in PCII, resulting in a net reduction of heat gain through the whole wall of 37.5% in PCI and 16% in PCII. The total heat flow through the stud area is reduced by 53.3% in PCI and 24.7% in PCII in comparison with the conventional wall; and the total heat flow through the insulation area is reduced by 11.9% in PCI but increased by 1.6% in PCII, resulting in a net reduction of total energy consumption through the whole wall of 25.7% in PCI and 7.1% in PCII.

The slightly better performance in PCII in comparison to the conventional wall is mainly attributed to the improvement over the stud area because of the extra ½" EPS covering the wood frame. The slightly higher thermal capacity of EPS insulation may have also contributed to the reduction of heat gain during the summer months.

Effective R-values based on the heat flux and temperature measurements are calculated for the heating dominant months from December 2008 to March 2009. A 20% stud area is assumed in the calculation using the following equation:

$$R_{effective} = \frac{1}{\dfrac{Q_f}{T_{i,f} - T_o} \times 0.2 + \dfrac{Q_{ins}}{T_{i,ins} - T_o} \times 0.8}$$

Where, Q_f is the heat flux through the stud area, W/m$^2 \cdot {}^o$C;

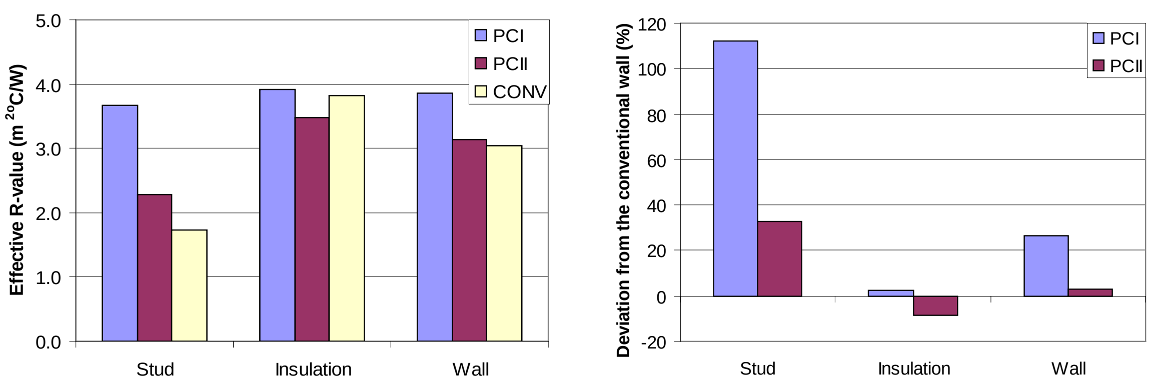
Q_{ins} is the heat flux through the insulation area, W/m$^2 \cdot {}^o$C;

$T_{i,f}$ is the interior surface temperature on the gypsum drywall over the stud area, ^{o}C;

$T_{i,ins}$ is the interior surface temperature on the gypsum drywall over the insulation area,^{o}C;

T_o is the exterior surface temperature on the siding, ^{o}C.

The results are plotted in Figure 5. The effective R-values of the stud areas are significantly improved in both PCI and PCII, by 112.3% and 32.7%, respectively. The R-value of insulation in PCII is 8.7% lower than that in the conventional wall; however, due to the improvement in stud area the effective R-value for the wall is increased by 2.9% in PCII.



(a) (b)

Figure 5. Effective R-values (a) and deviation from the conventional wall (b) calculated using the data from December 2008 to March 2009.

Temperature measurements

Surface temperatures of the interior gypsum drywall are compared since the surface temperature will have an impact on the risks for condensation, mold growth, and thermal comfort of the occupants. Two months, July for summer and December for winter, are chosen for the comparison. Figure 6 shows the interior surface temperatures on the gypsum drywall over the stud areas in July 2009. As shown in Figure 6, the surface temperature over the stud area in the conventional wall fluctuates much more and is higher during the daytime by a maximum of 1.1°C and lower during the night by a maximum of 0.6°C than the other two walls. The interior surface temperature over the stud area in PCI is slightly higher than that in PCII, but the difference is very small, within 0.2°C. The 1-1/2" air space in PCII and the extra 1" EPS in PCI have contributed to the lower surface temperature. The lower surface temperature is also an indication that the thermal bridging effect by the wood stud has been significantly reduced in the prefabricated wall systems.

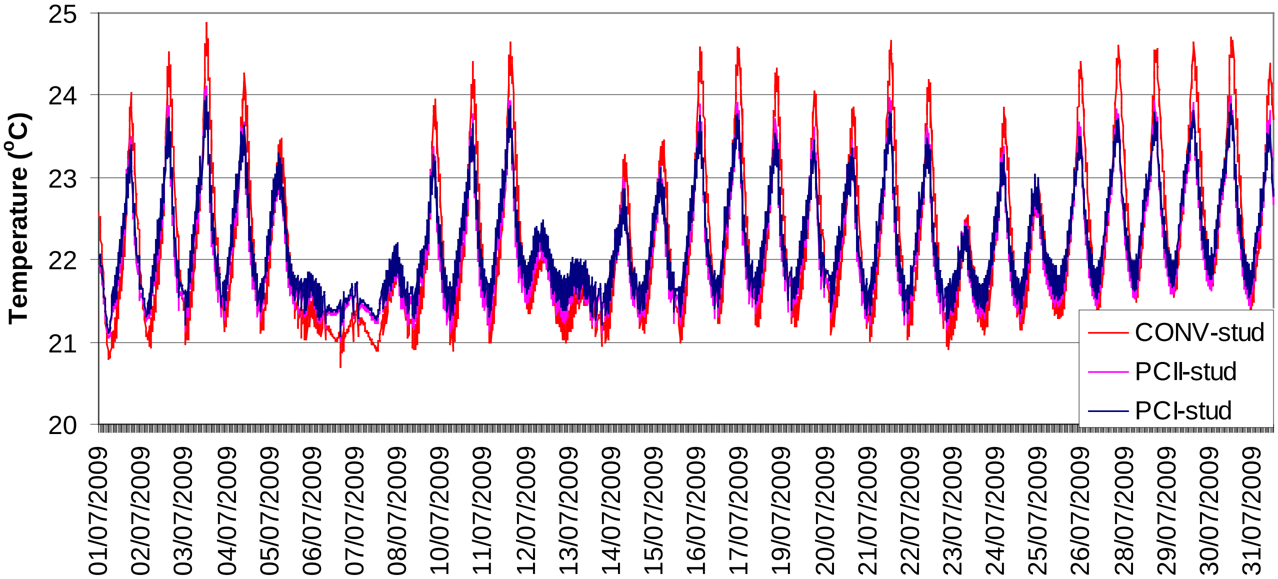


Figure 6. Interior surface temperatures on the gypsum drywall over the stud areas for the three test walls in July 2009.

The comparison of interior surface temperature over the stud area in the winter month of December 2008 is shown in Figure 7. The interior surface over the stud area of the conventional wall is colder than that in prefabricated wall systems, with an average of 0.6°C and a maximum of 1.2°C. The interior surface over the stud area in PCI is slightly warmer than that in PCII, within 0.2°C. The difference in the interior surface temperatures over the insulation areas among these three walls are very small, within 0.1°C, for both winter and summer months.

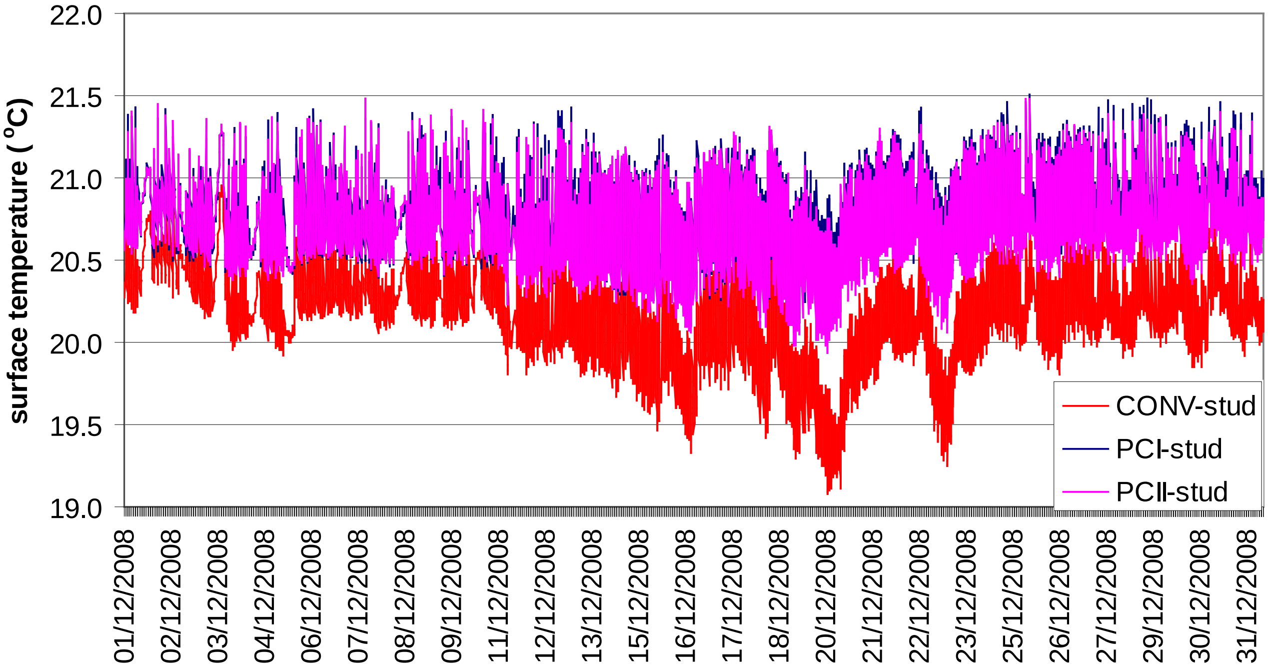


Figure 7. Interior surface temperatures on the gypsum drywall over the stud areas for three test walls in December 2008.

CONCLUSIONS

The effective thermal efficiency of two prefabricated wall systems are evaluated in comparison with the conventional 2x6 wood frame wall through one year's field monitoring on BCIT's Building Envelope Test Facility. One year's heat flux measurements show that, in comparison with the conventional 2x6 wood frame wall, prefabricated wall system I has 22.9% less heat loss and 37.5% less heat gain, resulting in a net 25.7% less heat flow, and prefabricated wall system II has 5.1% less heat loss and 16% less heat gain, resulting in a net 7.1% less heat flow. The improvement of thermal efficiency in prefabricated wall systems is mainly attributed to the significant improvement over the stud areas. Estimated effective R-values over the winter months from December 2008 to March 2009 show that the stud R-value in wall system I is improved by 112.3% with only a 2.6% improvement in the R-value over the cavity insulation, resulting in a net improvement of effective wall R-value by 26.5%; and the R-value at stud in system II (4" EPS infill in wood stud cavity) is improved by 32.7% while the R-value at cavity insulation is reduced by 8.7%, resulting in a net improvement of effective wall R-value of 2.9% under the testing conditions from September 2008 to August 2009. The field measurements show that the thermal performance of a 4" EPS infill in the wood stud cavity is comparable to the conventional 2x6 wood frame with a nominal R-20 fiberglass insulation. With the addition of 1" EPS over the 4"EPS stud cavity infill, the thermal performance is significantly improved.

Temperature measurements show that the interior surface temperatures over the stud area in the conventional wall fluctuate much more and are higher during the summer months and lower during the winter months compared to the prefabricated systems due to the thermal bridging effect of the stud. The 1-1/2" air space in prefabricated system II and the extra 1" EPS in prefabricated system I have significantly reduced the thermal bridging effect of the stud.

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