Graphical Method for Characterization of Space Conditioning Requirements for a House with Improved Building Envelope

Alexandra Giroux, Michael Collins, and John Wright
Department of Mechanical and Mechatronics Engineering, University of Waterloo, Waterloo, Ontario

Abstract

The current work examines the space conditioning requirements of HVAC systems for energy efficient construction and provides a visual method of comparing these loads. ESP-r simulations were used to compare the effect of energy efficiency on the heating and cooling loads of two homes located in Toronto, Ontario, examining the sensible and latent loads on the equipment. By tightening the building envelope and increasing the insulation, it was expected that a reduction in the sensible and latent loads would be seen, as well as a shift from large sensible loads to large latent loads. This shift will be illustrated using a graphical method that was developed for this purpose.

Details regarding how the sensible and latent loads are affected by increased insulation and reduced infiltration will enable better characterization of the space conditioning loads and allow for humidity control strategies to be identified and implemented. It will also indicate which types and capacities of HVAC equipment are required to maintain thermal comfort with an improved envelope.

Two cases were simulated. The first was a 'reference house' built to the specifications of the 2006 Ontario Building Code. The second was similar except that the house was upgraded to be very energy efficient, featuring increased insulation, reduced infiltration, and better windows. Preliminary results show that increasing the energy efficiency of the building envelope and decreasing the infiltration will have an appreciable effect on both the sensible and latent loads, as well as the sensible heat ratio of the equipment. These effects are shown using the graphical method developed.

1 Introduction

It is widely known that by reducing air infiltration through a houses envelope, the sensible heating and cooling loads on that house will also be reduced, but not much is known about how this will affect latent loads within the house. Much has been written about the importance of humidity control and the equipment that can be used to provide such control (Canada Mortgage and Housing Corporation 2009, Dieckmann 2008), and there is monitored data available for sensible heating loads (Doiron et al. 2011). Only one work that examines latent conditioning loads was found in the literature, and it deals exclusively with dehumidification and sensible cooling in the United States (Harriman III et al. 1997). No similar literature for the Canadian climate was found.

Previous Work

The previous work on this subject can be divided into work done on determining infiltration rates for current construction, and work done to determine loads on a home that can in turn be used to create occupancy and casual gain schedules for use in simulations. A report written for the Ministry of Municipal Affairs and Housing (MMAH) of Ontario presents measured infiltration rates for houses in Ontario. In 2009 testing was conducted on 100 houses in Ontario as part of a study to evaluate typical infiltration levels of the current Ontario housing stock (Harris 2009).

Lukas Swan's PhD thesis (Swan 2010) on developing ESP-r models of current Canadian housing stock provided a great deal of background information for this work. Swan's research developed a new, detailed model of energy consumption and greenhouse gases emissions using an extensive survey of the current Canadian housing stock. The database used to develop the model contains nearly 17000 entries of detailed construction and operational information about houses in Canada. The information in the databases concentrates on the energy requirements for space conditioning a home, in addition to other points of energy consumption, such as appliances, lighting, and hot water heating. This research provided a basis for the occupancy schedule used in the current study.

Pietila (Pietila 2011) provides a comprehensive picture of the electricity consumption of residential appliances and lighting. From this it can be assumed that the entire electricity draw for each appliance is converted into heat gains within the space, providing the basis for the casual gains schedule that was used for the current study.

A paper by Dieckmann (2008) examines how the Sensible Heat Ratio (SHR) changes for building envelopes of different eras, in seven different climate zones in the United States (Dieckmann 2008). The SHR is the ratio of the sensible load to the total load for the zone. Dieckmann examined how improvements in the minimum level of building envelope performance have influenced the SHR within mid-size commercial buildings. Improvements to building envelopes have reduced the sensible loads within the building, but latent loads are affected by ventilation rates, infiltration through the building envelope, and the presence of occupants within the building (Dieckmann 2008).

Multiple papers have been written examining the effects of tighter building envelopes and controlled ventilation on hot-humid climates in the Southern United States (Lstiburek 1993, Rudd & Henderson 2007). All the literature found emphasized the need for mechanical ventilation with tighter building envelopes along with some sort of humidity control scheme, but the literature focussed on hot-humid climates in the United States, and the methods of humidity control varied widely. Literature for Canadian housing stock tended to focus on the effectiveness of equipment that was added after the occupants encountered problems with air quality or humidity (Canada Mortgage and Housing Corporation 2009).

In 2010 Canadian housing stock had an average infiltration rate of 4.4 air changes per hour (ach) at 50 Pascals (Swan 2010). The MMAH study discussed earlier found that the average air leakage of the current Ontario housing stock is 3.14 ach when tested at 50 Pascals, with slightly lower results obtained for detached housing units and slightly higher air leakage for attached units (Harris 2009). For the ESP-r simulation of the houses in the current study, the AIM-2 model was used with ESP-r's predefined infiltration rates of 4.55 ach at 50 Pa for the reference house, and 1.5 ach at 50 Pa for the energy efficient house. For comparison, to meet the R-2000 standard a house cannot exceed 1.5 ach at 50 Pa (Natural Resources Canada 2012).

Objective

The objective of the current project is to develop a visual representation of these requirements, and demonstrate its use. A "rosette" showing all of the load lines for an annual simulation placed on a psychrometric chart was developed to show how the equipment loads will change throughout the year as the energy efficiency of a house is increased. This work compares the latent and sensible loads of a reference house built according to the 2006 Ontario

Building Code to an energy efficient house that was built with better insulation, higher quality windows, and more air tight construction. The rosette was overlaid on a psychrometric chart to visually demonstrate the changes in latent and sensible heating and cooling loads as changes to the building envelope are made.

This approach allows for visualization of the building loads. In particular, it shows whether the equipment load is dominated by sensible loads or latent loads for a given time period. In future work, examining the rosette and how the load lines change between seasons, or with different outdoor conditions, and analysis of the SHR throughout the year, will allow for better design of residential HVAC systems.

In particular this graphical approach allows for examination of the latent load that is a direct result of infiltration through the building envelope. To improve the energy efficiency of a building or home, the infiltration can be reduced significantly by providing a continuous air barrier and by sealing the building envelope at points that are typically "leaky" or "drafty" such as around windows and between floors. Infiltration is considered to be a dominant source of moisture in houses located in humid climates, and reducing infiltration is expected to have a significant impact on the latent loads within the house. For the reference house, for example, infiltration is expected to provide most of the humidity control (i.e. removal) for the conditioned space.

2 ESP-r Model Design and Simulation

Reference House

The floor plan of the house simulated in this work is based on the house design presented in Building Science Corporation's (BSC) Very Cold Climate Case Study (Building Science Corporation 2006). This case study provides detailed design and simulation results for a two story, 110 square meters (1190 square feet) house located in Juneau, Alaska. The Juneau house floor plan was used as it is not complicated and can be easily modified. For the current study, the house was located in Toronto, Ontario, was built using slab on grade construction so there is no basement, and all construction details for the reference version of the house were chosen to be in line with the 2006 Ontario Building Code. Validation of the model was achieved by comparing the ESP-r simulations results to estimates of the sensible heat losses using the degree-day method.

The reference house consists of a single zone, using an idealized plant to condition the space, and is already quite energy efficient compared to earlier housing standards. The AIM-2 model was used to provide a realistic model of infiltration through the building envelope. For the reference house, ESP-r's pre-defined value for average air infiltration, 4.55 ach at 50 Pa, was used. To ensure that the house met ASHRAE 62.2 (2013) a scheduled air flow of 38 L/s was drawn in to the house. This outdoor air was not pre-conditioned before it was drawn into the house.

The building envelope was modelled in multi-layer assemblies that meet the thermal insulation requirements set out in Section 9.25.2 of the 2006 Ontario Building Code. The minimum level of insulation for above-grade walls is RSI 3.34, or R-19. The floor and roof minimum insulation levels of RSI 1.41 and RSI 4.93 are also met.

To allow for flexibility when simulating the windows in the reference house, the Complex Fenestration Construction (CFC) implementation developed by Lomanowski (2008) was used. Window assemblies were constructed in GSLEdit and imported into ESP-r using the procedure described in (Lomanowski 2008). The windows used in the reference house model are double pane, air-filled windows. No low emissivity coating was used for the reference house. From GSLEdit, a 0.5 inch light aluminium venetian blind was selected. The blinds use horizontal slats, and are left at an angle of 45° for the simulation. Dynamic shading controls were not used in this model. The U-value for this window is 1.85 W/(m^2-K). The window frames were not included in the model.

Occupancy and casual gain schedules were created based on data taken from (Swan 2010) and (Pietila 2011). The schedule represents two people living in the house, who are gone during regular working hours from Monday to Friday. It was assumed that the electrical draw for each appliance is completely converted to heat within the conditioned space (Pietila 2011). The occupancy and casual gain schedules were created on an hourly basis and the same schedules were used for both the reference house and the energy efficient house.

Energy Efficient House

Once the reference house was modeled, an energy efficient version of the house was considered. The energy efficient house used the same geometry and location as the reference house. The house assemblies were upgraded to represent much higher levels of thermal insulation. The thickness of the insulation within all building assemblies was doubled, and the infiltration rate used in the AIM-2 model was reduced from 4.55 ach at 50 Pa to 1.5 ach at 50 Pa. A heat recovery ventilator (HRV) was also added. In a real house, reduced infiltration can be achieved by paying careful attention to locations such as headers, cantilevered floors, fireplaces, basement walls, and any penetrations of the building envelope, such as those required for utility conduits. Doubling the thickness of the insulation in the walls from 100 mm to 200 mm brings the insulation rating from RSI 3.34 (R-19) to RSI 6.68 (R-38).

The windows were upgraded significantly, from double paned air filled windows to triple paned, argon filled windows with low-emissivity coatings (ε=0.157) on surfaces 2 and 5. The U-value for this window construction is 0.65 W/(m^2-K). As with the reference house, window frames were not modelled explicitly.

The main difference between the reference house and the energy efficient house is that in order to maintain indoor air quality, mechanical ventilation must be added instead of relying solely on infiltration to bring fresh air into the house. To further reduce the energy required to condition the house, a Heat Recovery Ventilator (HRV) was added to the model. The HRV pre-heats the outdoor air being drawn into the system using heat from exhaust air.

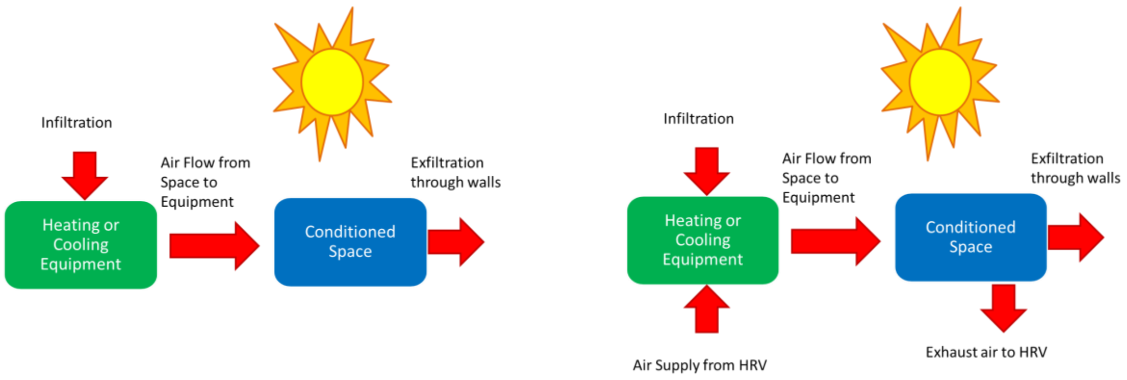

Figure 1: Diagrams showing the air flows for the reference house and the energy efficient house with HRV

The least complex way to incorporate the HRV into the model is to set up two dummy zones outside of the house (Strachan 2013). The first dummy zone represents the exhaust side of the HRV, and the second dummy zone represents the supply side of the HRV. These two zones provide air flow to and from the house. The exhaust zone will determine the temperature to which the supply zone will heat the exterior air before it is drawn into the house. An

HRV with 75% effectiveness was selected, and a mechanical ventilation rate of 38 L/s of ventilation is required to meet ASHRAE 62.2 (2013) requirements. This ventilation is drawn in to the house through the HRV, and does not include infiltration through the building envelope.

Table 1: Summary of air flows between zones in Energy Efficient House Model

Zone	Infiltration (L/s)	Ventilation (L/s)	Zone providing Ventilation Air
Main	AIM-2 model	38	Supply
Exhaust	9.5	28.5	Main
Supply	38	0	N/A

Modelling the HRV using the two dummy zones allows the correct amount of moisture to be drawn into the house zone, since ambient air is drawn into the supply zone, heated and supplied directly to the house without adding or removing any moisture. Simply reducing the airflow into the house by a factor determined by the selected HRV efficiency also reduces the amount of moisture being delivered to the conditioned space, and will give inaccurate results.

The same occupancy and casual gain schedules are used for both the reference house and the energy efficient house.

3 Simulation Results

Rosette Development

The rosettes that are used to present the simulation results show the loads on the HVAC equipment that must be met to bring the house to the desired condition point. The head of the load line is located at the condition of the house zone, as determined by the set points chosen for the simulation as shown in Figure 2. The location of the tail of the load line represents both the magnitude of the load and the SHR at that time step, as the load line is plotted using both the sensible and latent loads from the ESP-r results.

Load lines in the lower left quadrant represent sensible heating and humidification, load lines in the upper left quadrant represent sensible heating and dehumidification, lines in the lower right quadrant represent sensible cooling and humidification, and finally, lines in the upper right quadrant represent sensible cooling and dehumidification. Horizontal load lines represent sensible heating or cooling only, with no latent load present for that hour, and load lines parallel to the isotherms represent humidification or dehumidification with no sensible load present for that hour. The empty box at the centre of the rosettes is defined by the set points that are used for the simulations.

When plotting the rosettes, a mass flow rate acts as a scaling factor that will determine the length of the load lines. By changing this mass flow rate, the length of the load lines will be scaled up or down. The flow rate that was used to plot the data presented below was selected to make the rosettes easy to read.

The lengths of the load lines are not the only important information obtained from the simulations. Equally important are the angle of the load line, and the frequency at which each load line occurs over the course of the year. The angle of the load line represents the SHR. – the steeper the angle of the load line the smaller the value of the SHR. It is expected that the reference house loads will be dominated by sensible loads, with a small humidification or dehumidification load needed to condition the space to comfort levels. Conversely, the energy efficient house, with increased thermal insulation, minimal infiltration and the addition of the

HRV, is expected to have much smaller SHR values. A detailed analysis of the SHR at each timestep is outside the scope of this paper, but will be included in future work.

The distribution of the load lines around the condition point is also a concern. To examine this, the loads are split up into a number of different load conditions, i.e. heating and dehumidification, and the number of hours that each load condition occurs is totalled for the entire year. This analysis only determines whether a load condition is present at a given timestep, not the magnitude of the load.

House Rosettes

The load lines for the reference house rosette account for both the sensible load and the latent load. The load lines represent the energy that must be added or removed by the HVAC equipment in order to condition the space. When the results from the reference house are plotted on the psychrometric chart, the rosette shown in Figure 2 is obtained, showing the load line for each of the 8760 timesteps in the year.

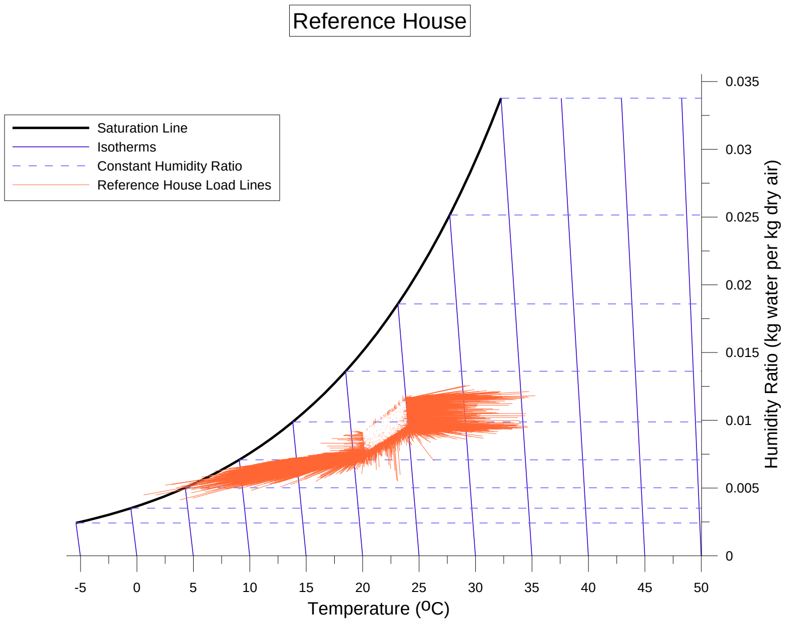

Figure 2: Load lines for reference house plotted on psychrometric chart

The load lines for the energy efficient house were plotted on the same psychrometric chart, using the same mass flow rate as the reference house (0.5 kg/s). This shows that the heating loads are reduced for the energy efficient house, but the cooling loads are still present. Also notable is a lack of any dehumidification loads to bring the relative humidity of the space down to the upper relative humidity limit imposed on the space.

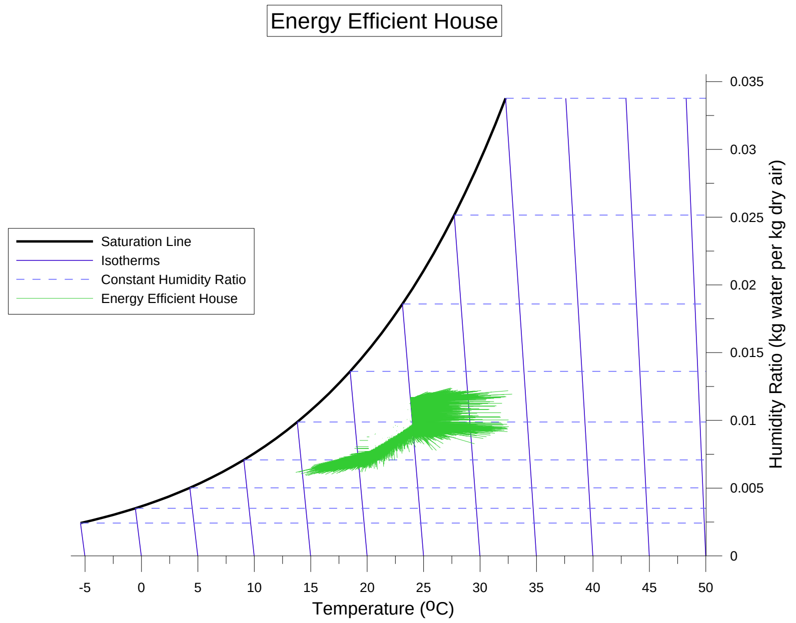

Figure 3: Load lines for energy efficient house plotted on psychrometric chart

For the energy efficient house, the load attributed to the HRV is not included in the calculation of the sensible and latent loads. The HRV conditions the air before it goes through the heating and cooling equipment, and it is the load on this heating and cooling equipment that is the concern.

When the plots shown in Figure 2 and Figure 3 are overlaid, the differences, especially in the sensible heating load, are clear.

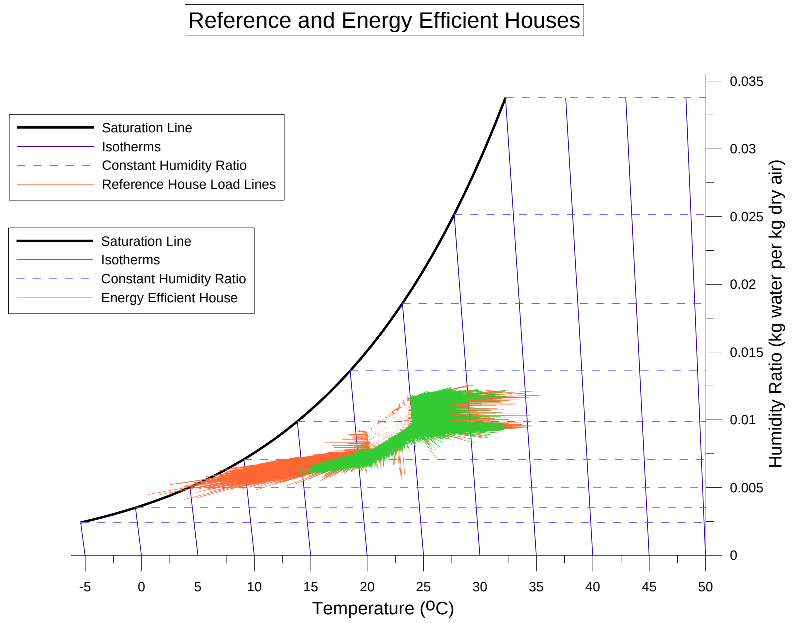

Figure 4: Load lines for reference and energy efficient houses overlaid on each other

The loads for the reference house are fairly even split between sensible heating and sensible cooling, and both humidification and dehumidification are required. The energy efficient house shows that cooling is required much more frequently, and dehumidification is rare.

With 8760 timesteps in a year, examining an entire year's worth of data on one rosette is not realistic. The data was separated into each season, for each house.

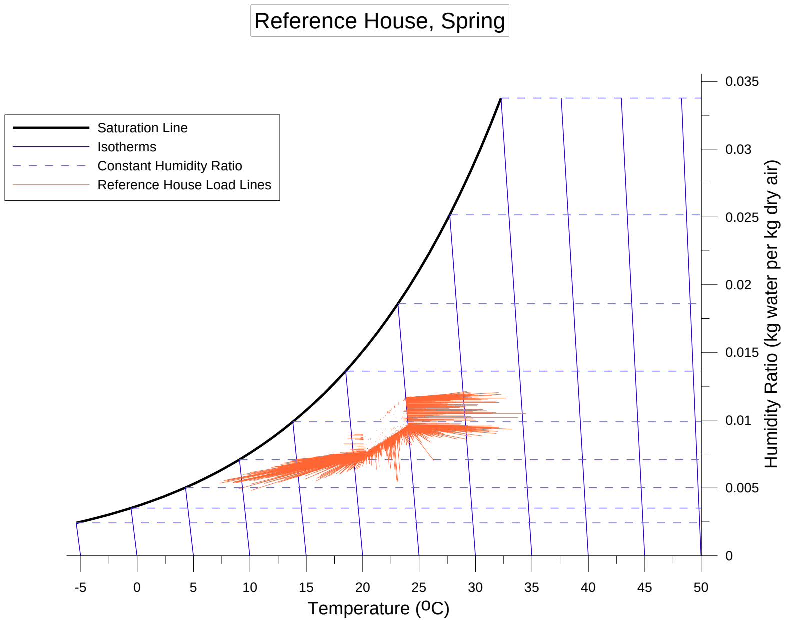

Figure 5: Load lines plotted for the reference house in spring (20 March to 20 June)

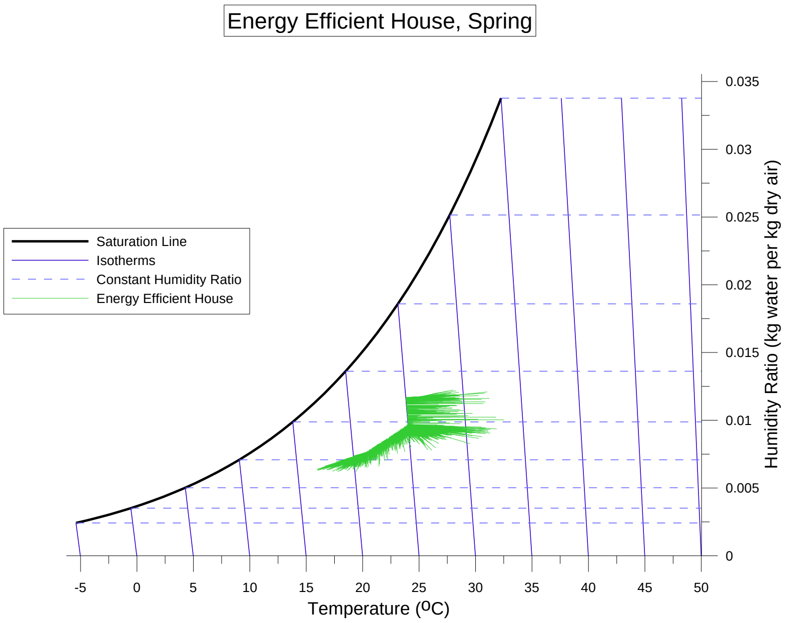

Figure 6: Load lines plotted for the energy efficient house in spring (20 March to 20 June)

The plotted load lines for spring are evenly distributed around the condition boundaries for the reference house, with many load lines showing that heating and humidification is required. For the energy efficient house, the load lines show that cooling and humidification is required during the spring, with a few load lines in the upper right quadrant showing a small amount of dehumidification required. The load lines for the energy efficient house are much more tightly grouped together than those of the reference house, and there is a small reduction in the length of the load lines for the more efficient house.

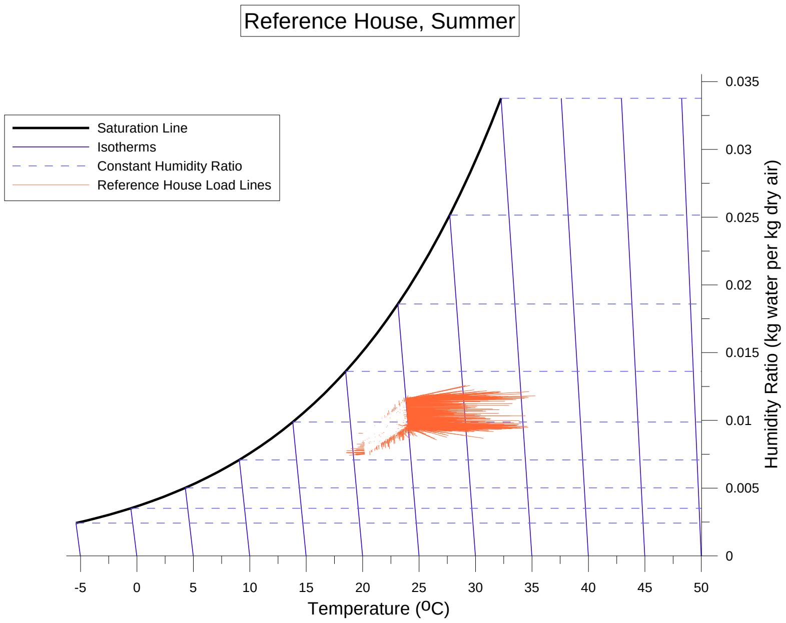

Figure 7: Load lines plotted for the reference house in summer (21 June to 21 September)

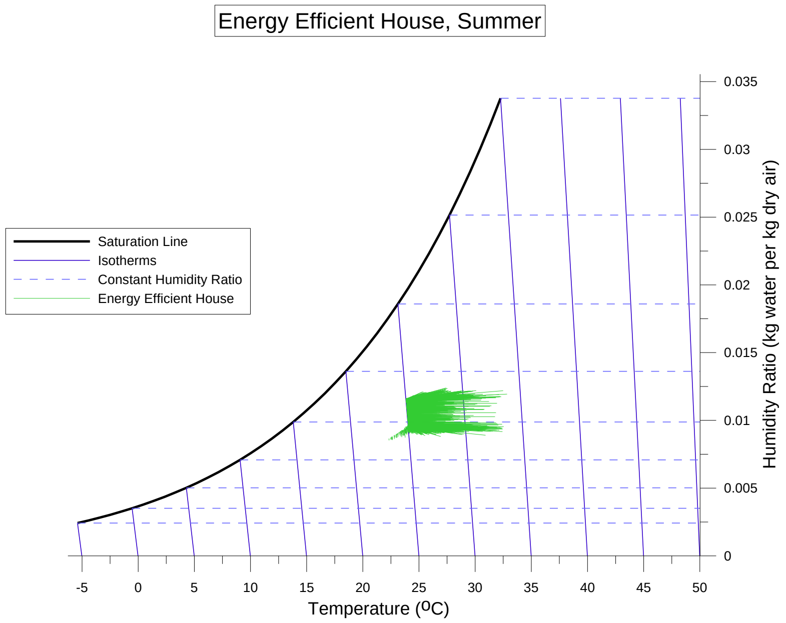

Figure 8: Load lines plotted for the energy efficient house in summer (21 June to 21 September)

In the summer, the reference house plot shows a small number of load lines showing sensible heating, as well as load lines showing humidity control with no concurrent sensible load. The lines for the energy efficient house are grouped very tightly together, and no sensible heating is required at all during the summer. However, the sensible loads for the energy efficient house are not accompanied by large latent loads during the summer. This suggests that during the summer the most significant source of moisture within the conditioned space is the infiltration through the building envelope.

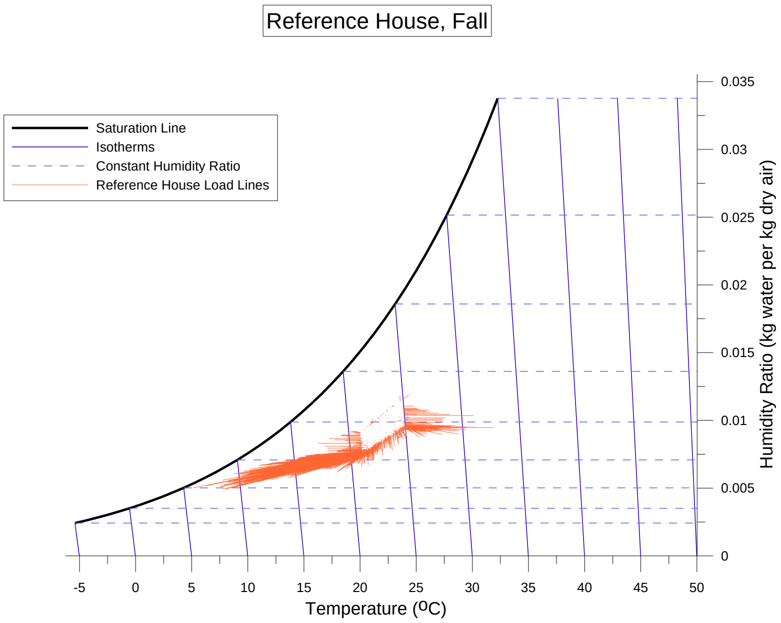

Figure 9: Load lines plotted for the reference house in fall (22 September to 20 December)

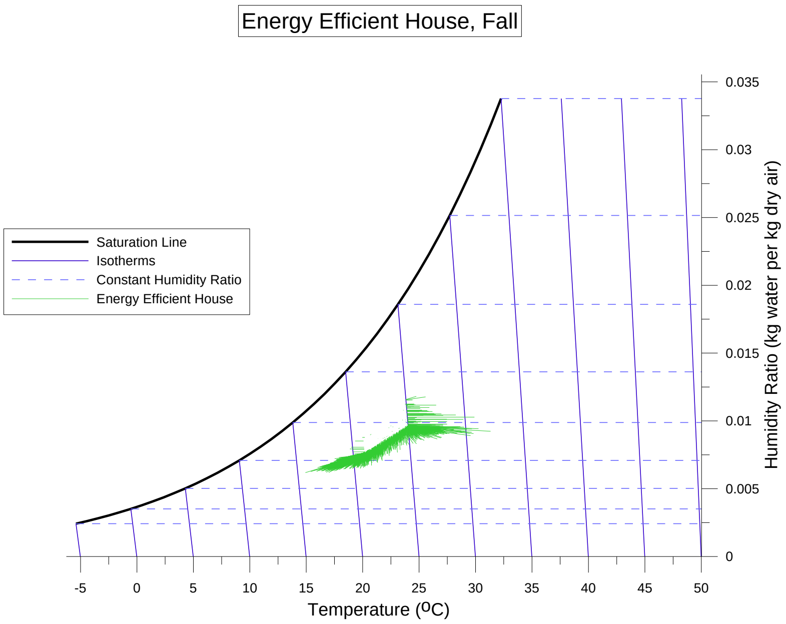

Figure 10: Load lines plotted for the energy efficient house in fall (22 September to 20 December)

For the reference house for the fall, the load lines show sensible heating humidification, and sensible cooling with small amounts of humidity control. The energy efficient house also shows times of both sensible heating and cooling, and many timesteps showing humidification. The load lines from the energy efficient house are more closely grouped together than the reference house.

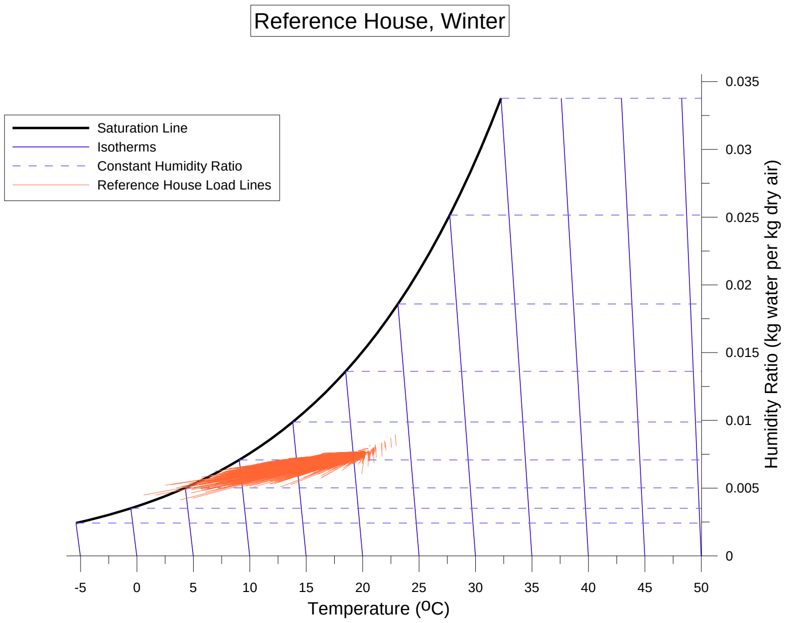

Figure 11: Load lines plotted for the reference house in winter (21 December to 19 March)

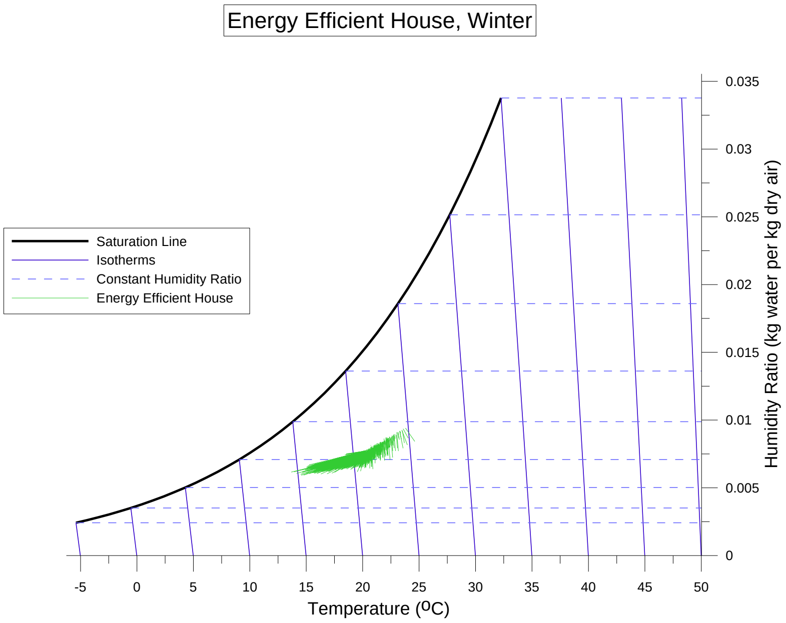

Figure 12: Load lines plotted for the energy efficient house in winter (21 December to 19 March)

Load lines for winter show heating and humidification is the main load condition for the reference house, while the energy efficient house also shows more timesteps where only humidification is required.

Another way to examine how the loads have changed between the reference house and the energy efficient house is to count the number of timesteps that a given combination of equipment is in use. All possible combinations of sensible and latent conditioning were listed, and the total number of hours in the year that each combination was present was calculated for each house. Ten different load combinations were considered. The first two load combinations, sensible heating and sensible cooling, include all hours where sensible heating or cooling is provided to the house zone, regardless of whether or not latent conditioning is present.

Table 2: Number of times in simulation that each load condition occurs

	Load Combination	*Hours of Load Combination*		*Percent Difference*
		Reference House	**Energy Efficient House**	
Heating	**Sensible Heating Only, No Humidification or Dehumidification**	116	7	94% decrease
	Sensible Heating with Humidification	4448	3170	29% decrease
	Sensible Heating with Dehumidification	7	0	100% decrease
	Total Hours of Sensible Heating	4571	3177	30% decrease
Cooling	**Sensible Cooling Only, No Humidification or Dehumidification**	9	15	67% increase
	Sensible Cooling with Humidification	1166	2326	99% increase
	Sensible Cooling with Dehumidification	880	774	12% decrease
	Total Hours of Sensible Cooling	2772	3863	39% increase
Latent Loads	**All Humidification**	6578	7168	9% increase
	All Dehumidification	964	774	20% decrease
	Humidification Only, No Sensible Loads	964	1672	73% increase
	Dehumidification Only, No Sensible Loads	77	0	100% decrease

This analysis does not take into account any changes in the magnitude of the load – while the number of timesteps for a given load condition may not change significantly, the magnitude of the load itself during those timesteps may be very different. For example, the case where sensible cooling and humidification is present showed a large increase in the number of occurrences but on closer examination of the data, this occurred when the sensible gains within the house were very high, or on cool, dry days during the summer, when insolation would provide heat gain within the house.

The energy efficient house shows reduced need for sensible heating (4571 hours versus 3177 hours), but more hours where sensible cooling is required (2772 hours versus 3863 hours). The total number of hours of humidification, provided with or without sensible heating or cooling, shows an increase of 590 hours between the reference house and the energy efficient house (6578 hours versus 7168 hours), while the hours of dehumidification is decreased by 190 hours from 964 hours to 774 hours.

4 Discussion

From the rosettes shown here, reducing the infiltration, increasing the insulation, and using higher quality windows will affect both the sensible and latent loads within a conditioned space. The energy efficient house with reduced infiltration showed reduced humidification and dehumidification loads, as well as reduced sensible heating loads. Sensible cooling is also slightly reduced, but the difference in magnitude is most notable for sensible heating. While the magnitude of the cooling loads is reduced, there are more hours where cooling is required to condition the house to the desired set points. This may increase the total amount of energy that is consumed by the cooling system in the house. While the reference house rosette shows an equal distribution of load lines around the condition set points, the energy efficient house has more load lines showing sensible cooling, and fewer load lines where dehumidification is required. Notably, dehumidification with no sensible load does not occur for the energy efficient house,

The rosette shows two distinct sections due to the difference in the heating and cooling set points, and the range in acceptable humidity levels. Overlaying the rosettes for the reference house and the energy efficient house shows the differences between the scale of the loads for the two houses, and the distribution of the loads. The rosettes also make the set points used in the simulations clearly visible.

When it comes to choosing and sizing equipment, the length of the load lines is not the only thing that should be taken into account. The differences in the distribution of the load lines will also affect equipment choices. For example, the load lines for the energy efficient house during the spring and fall are more tightly grouped together than the reference house. The reference house may require heating during the shoulder seasons, while the energy efficient house may not. This should be taken into account when selecting and sizing equipment for the energy efficient house. The differences in the sensible – latent split of the two houses may require the sensible and latent conditioning systems to be designed as two independent systems, rather than one system that provides both sensible and latent conditioning.

5 Conclusions

The work presented here has shown that adding energy efficiency measures to a home in Toronto will impact both the sensible and latent loads, as expected. As well as reducing the magnitude of the loads, increased insulation and reduced infiltration will also reduce the number of hours in the year where sensible heating is required and increase the number of hours where sensible cooling is required. The graphical method presented here provides a visual representation of this analysis, showing both the frequency and magnitude of each load on one plot.

The rosettes presented here are representative of one particular house design, in one particular location (Toronto), using one occupancy schedule and control scheme. To draw more general conclusions, more cases will need to be simulated. There are many other cases that could be considered as part of future work on the characterization of sensible and latent loads. One case that could be considered is to increase the number of occupants in the house, adjusting the occupancy and casual gain schedules accordingly. Other cases could include different set points and control methods for temperature and relative humidity. In addition, more dramatic differences are expected if the reference house was built to meet an earlier building code.

Another case that should be examined is the effect of adding dynamic shading to the model. Both the reference house and the energy efficient house presented here have shading incorporated through the use of CFCs, but the blinds modelled are left in the same position all day. The use of a dynamic shading model may further reduce sensible heating and cooling loads, while maintaining similar latent loads. Dynamic shading is also a more realistic case than static shading, as occupants are likely to open or close window blinds to maintain comfort within the space.

In addition to these cases that have yet to be considered, other locations and climates within Canada will also be simulated. All of these cases will be analysed using the graphical method presented here.

6 Acknowledgements

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