Modified Air Circulation: Energy Savings and Indoor Air Quality

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ABSTRACT

An experiment at the Canadian Centre for Housing Technology (CCHT) showed that most of the energy savings achieved by more efficient furnace fan motors can be obtained by using low-cost, commercially available, programmable fan controllers with standard (PSC) motors. Energy efficient fan motors (brushless DC, or ECM) can save up to 75% of fan energy, but they are expensive, and retrofits to existing furnaces are not practical. The fan controllers are easy to install in houses with standard fan motors.

The identical CCHT houses have mid-efficiency gas-fired furnaces with PSC motors. The experimental house was fitted with a fan controller while the control house continued to operate normally. Four different furnace fan schedules were run in the experimental house, and the consumption of furnace natural gas and electricity were monitored for several days in each schedule. To investigate possible effects on indoor air quality and comfort, carbon dioxide (CO_2) was released in both houses, and CO_2 levels and temperatures at several points were compared.

The fan controller produced 49% to 65% reductions in furnace fan electricity, and 7% to 10% increases in furnace natural gas use, when compared with continuous circulation. This fuel switching results in net savings to homeowners, and if the saved electricity is fossil fuel generated, it results in net reductions of greenhouse gas emissions. CO_2 levels did increase, but remained well below Health Canada limits, and within levels generally observed in Canadian houses. There were no statistically significant differences in temperatures.

Introduction

Recent projects at the Canadian Centre for Housing Technology (CCHT) demonstrated the effects of energy efficient furnace fan motors (Gusdorf et al. 2003). Electronically commutated motors (ECM) were shown to reduce total house electrical consumption by 25% during the heating season, and to reduce electricity for cooling by 10%, when used with continuous circulation. During heating, extra natural gas was consumed to balance the reduced heat from the furnace fan motor. The net effect is a significant reduction in utility bills (electricity and natural gas). If the saved electricity is from coal-fired plants, then there is a significant net reduction in greenhouse gas (GHG) emissions. Enbridge Gas Distribution (EGD), an Ontario natural gas utility which was a sponsor of the CCHT projects, now has a successful program to promote the installation of furnaces with ECM fan motors.

However, ECMs and similar motors are only a practical option in new furnaces. Retrofitting existing furnaces with a new motor involves significant labor, and raises warranty and liability issues. For this reason, one of the authors (Simpson) suggested that a low-cost, commercially-available device could provide at least some of the benefits of energy-efficient fan motors with existing furnaces. These programmable fan controllers cost about $100, operate on low voltages, and can be installed by homeowners. They cause the furnace fan to run in circulation speed after it has been off for a user specified time, and then keep it in circulation speed for a specified time or until there is another call for heating or cooling.

To test the effects of the programmable fan controller, one of the two identical CCHT houses was designated as the control house, and was run in continuous circulation throughout the tests. The other – the experimental house – was operated in four different circulation modes. In both houses, the furnaces had conventional PSC motors.

Enbridge Gas Distribution and The Regional Municipality of York are interested in the possible application of fan controllers to houses built in the 1990s. These houses tend to be reasonably airtight, and therefore can benefit from increased air circulation, although they may not require continuous circulation. Their airtightness is generally around 3.5 air changes at 50 Pascals of depressurization (3.5 ach@50Pa). The CCHT houses are R-2000 houses and are significantly more airtight – around 1.1 ach@50Pa. For this reason, the CCHT houses were loosened by opening their windows slightly.

Daily totals of furnace electricity and natural gas consumption were used to determine any differences due to circulation modes. In order to measure the effects of the fan controller on air circulation within the houses, carbon dioxide was released and measured within them. CO_2 was released at three points in each house, at a total rate equivalent to four people at rest. The levels of CO_2 were monitored at three points in each house, and the levels and differences between them were analyzed to determine differences in circulation due to the circulation modes. Inadequate circulation can result in some parts of a house being slightly warmer or cooler than others, so temperatures at several points in each house were measured and analyzed to see if they varied by circulation mode.

Ventilation, Circulation, Indoor Air Quality & Fan Controllers

Ventilation can be defined as the movement of air into and out of a building. In ventilation, fresh air from outside the building replaces inside air, thus removing contaminants generated inside the building such as excess humidity and carbon dioxide, and volatile organic compounds. Ventilation can be due to natural infiltration, duct leakage if ducts are located outside the envelope, or mechanical ventilation by exhaust fans or heat recovery ventilators (HRVs). In this project, ventilation was almost entirely due to natural infiltration since there are no outside ducts, and the HRVs were turned off and sealed. A small amount of mechanical ventilation was provided by the stove hoods and clothes dryers. Circulation can be defined as the movement of air within a building. For the purposes of this project it is the movement of air caused by the furnace fan. Circulation does not remove contaminants from a building, but it can prevent excessive local concentrations by distributing the contaminants more evenly throughout the building.

The programmable fan controller sets the maximum amount of time that the furnace fan will be off each hour. For example, one of the settings, or modes, used in this project was 30 minutes off and 30 minutes on. If the thermostat causes the furnace to run at least once every 30 minutes, then the fan controller has no effect. But if 30 consecutive minutes pass without the thermostat causing the furnace to run, then the controller will cause the furnace fan to run for up to 30 minutes, or until the thermostat calls for heat again.

How much effect, if any, the fan controller will have on circulation during any hour or day depends on the off and on times it is programmed for, and the amount of time that the thermostat keeps the furnace running. When there is a high demand for heat, then the controller may have no effect, especially if it is set to a long maximum off time, such as 45 minutes. The effects of ventilation and circulation were separated as much as possible by keeping the circulation mode in the control house constant while using the programmable fan controller to vary it in the experimental house.

Poor indoor air quality in reasonably airtight houses is mainly a concern during the "shoulder seasons" (and during the summer if windows are kept closed). During cold weather, the temperature differences between the inside and outside of a house are generally enough to ensure good ventilation, and the furnace will run often enough to provide good circulation. But during the spring and fall, when windows are closed and the furnace runs only occasionally, inadequate ventilation and circulation can be a problem. Because the effects of a programmable fan controller depend on the length of time the furnace is off, they should be greatest during the shoulder seasons – precisely when more circulation may be needed.

The originator of the fan controller concept (Rudd 2004) supplied the CCHT with three different models.* All three can control a motorized damper in a fresh air duct to the furnace return plenum, as well as the furnace fan. Thus, the controllers can increase ventilation as well as circulation. Ventilation control was not used in this project because the target houses with 3.5 ach@50Pa do not require mechanical ventilation.

Methodology

One of the two identical CCHT houses was defined as the control house, and the other was defined as the experimental house. The general methodology of this project consists of the following:

- Open windows in both houses, and do blower door tests, to bring their airtightness levels as close as possible to 3.5 ach@50Pa, to match houses built in the 1990s.
- Use the thermostat and programmable fan controller to produce four circulation modes in the experimental house while keeping the circulation mode in the control house constant.
- Release equal amounts of CO_2 in both houses at a rate representative of four people.
- Measure electricity and natural gas use by the furnaces, the amount of time the furnace fan spends in heating and circulation speed and the airflow rate in each speed, CO_2 levels at three points, and temperatures at various points in both houses.
- Analyze the effects of the four circulation modes in terms of differences between the control and experimental houses. The differences to be analyzed are:
    - Electricity use by the furnace.
    - Natural gas use by the furnace: As the furnace fan uses less electricity, and therefore puts less heat into the air, more natural gas should be needed to maintain the house at its temperature set point.
    - Daily circulated air volumes: The amounts of time that the furnace fans spend in heating and circulation speed, and the airflow rate for each speed are used to determine the total volume of air circulated through the furnace of each house

* See www.fancycler.com, www.aprilaire.com or www.scillc.com.

each day. These are combined to get minimum, mean and maximum volumes for each circulation mode.

- Temperatures: If a given circulation mode causes the furnace fan to run for a smaller amount of time, then it is possible that some points in the house will become warmer or cooler than others. This is the first method for evaluating the circulation and distribution effects of the circulation modes.
- Carbon dioxide levels: If a given circulation mode causes the furnace fan to run for a smaller amount of time, then it is possible that CO_2 levels will be higher in the places where it is released, and that the differences between these places and others will be greater. This is the second method for evaluating the circulation and distribution effects of the circulation modes.

Making the Houses Less Airtight

The attic hatch, two ducts in the basement, and all windows except those in the master bedroom were opened slightly, using a quick repeatable method. Two blower door tests were done on each house, and the average results are 3.54 ach@50Pa for the control houses, and 3.50 ach@50Pa for the experimental house.

The Four Circulation Modes

The programmable fan controller and house thermostats were used to create four different circulation modes in the experimental house, which was run for ten days in each mode. Listed by increasing maximum off-times, these are:

- *Continuous circulation*. In this mode, the furnace fan runs in circulation speed whenever there is no demand for heat. Thus, the fan is always running, either in heating or circulation speed.
- 30 minutes off / 30 minutes on (*30/30*). The controller is programmed to allow the furnace fan to be off for 30 consecutive minutes, then to be run in circulation speed for 30 minutes or until there is a demand for heat.
- 45 minutes off / 15 minutes on (*45/15*). The controller is programmed to allow the furnace fan to be off for 45 consecutive minutes, then to be run in circulation speed for 15 minutes or until there is a demand for heat.
- *No circulation*. The furnace fan runs only when there is a demand for heat.

The furnace fan motors have four speeds. During heating, they run at the second highest speed, and during circulation they run at the lowest. The thermostats in both houses were kept at a constant 21°C (70°F).

Carbon Dioxide & Circulation

Half of the CO_2 release occurred in the master bedroom, which was the only room in which the window was not opened. Thus, the highest CO_2 levels were expected to be in the master bedroom, and CO_2 was measured there. One thousand parts per million (1000 ppm) of CO_2 is an ASHRAE guideline which is often used as the level at which criteria for comfort (odour) is likely to be met (ASHRAE 1989), although levels below 3,500 ppm are not believed to pose any health risk to humans (Health Canada 1987). Thus, circulation modes that often result in master bedroom CO_2 levels above 1,000 ppm can be considered to provide less than adequate circulation. Circulation was also evaluated by comparing the differences between the master bedroom CO_2 levels in the two houses, and by comparing the differences between the levels in the master bedroom and other locations in which CO_2 was not released.

CO_2 levels in Canadian houses. While the ASHRAE guideline of 1,000 ppm is a generally accepted target for maximum CO_2 levels, it may also be useful to look at some levels that have been observed in occupied Canadian houses. A review of data collected in occupied houses for Natural Resources Canada and Canada Mortgage and Housing studies (CMHC 1994, CMHC 1995) shows that weekly averages above 1,000 ppm are fairly common. This implies that peaks above 1,000 ppm are even more common. Thus, while the guideline of 1,000 ppm may be a desirable target, it is often exceeded in actual houses without apparent harm or discomfort to the occupants.

The CO_2 release rate. The CO_2 release rate simulated the amount produced by four people at rest. Each person produces approximately 0.31 litres per second (L/s) of CO_2 (ASHRAE 1989), so the total release rate for each house was set at 1.24 L/s. Half of this was released in the master bedroom located upstairs. 25% was released in the bedroom in the northwest upstairs corner, and the remaining 25% was released in the dining room in the northwest corner of the ground floor.

Results

Effects of the Circulation Modes on Fan Operation & Circulation

Table 1. Total Circulated Air Volumes (m^3/day), and Differences Between Means

Conditions in Experimental House	Experimental House			Control House (Continuous Circulation)			Mean Exp/Con
	Min	Mean	Max	Min	Mean	Max	
Continuous	46,697	46,697	46,697	46,177	46,177	46,177	101.1%
30/30	18,485	19,427	20,648	42,851	43,574	44,194	44.6%
45/15	10,338	14,257	27,826	40,905	43,447	47,815	32.8%
No Circulation	3,696	14,617	27,798	42,048	44,744	48,001	32.7%

The experiment occurred between March 9 and May 11, 2004. Each circulation mode was run for ten days, divided into two periods separated by at least three weeks to provide a variety of weather conditions. Average outdoor temperatures ranged from 2.0°C (36°F) for *no circulation* to 7.7°C (46°F) for *45/15*.

Given the daily amounts of time the furnace fan spent in heating and circulation speed, and the airflows for each speed, one can calculate the amounts of air circulated through each house each day. The results are analyzed by circulation mode, and shown in Table 1. As expected, there is no systematic variation in the control house. In the experimental house, the volume of circulated air generally decreases with circulation modes with longer maximum off-times. The exceptions to this pattern are the mean and maximum volumes, which are slightly larger (or virtually equal) in *no circulation* than in *45/15*. The exceptions are due to the fact that the amount of time the furnace fan spends in each speed is a function of heating load as well as the fan controller programs. However, the minimum volumes in the experimental house do decrease as expected, and some measures of circulation may be more dependent on the minimum volumes than they are on the means.

Given the above factors, one would not expect the differences in natural gas use or circulation to be as significant or consistent as they would be if circulated volumes had varied regularly with circulation mode. One might expect that some differences would depend more on the minimum volumes of circulated air, and would vary regularly with maximum off-times. Others might depend on mean volumes, and would show large differences between *continuous circulation* and *30/30*, smaller differences between *30/30* and the last two modes, and little or no differences between the *45/15* and *no circulation* modes.

Figure 1. Total Circulated Air Volumes vs. Furnace On Times, By Days

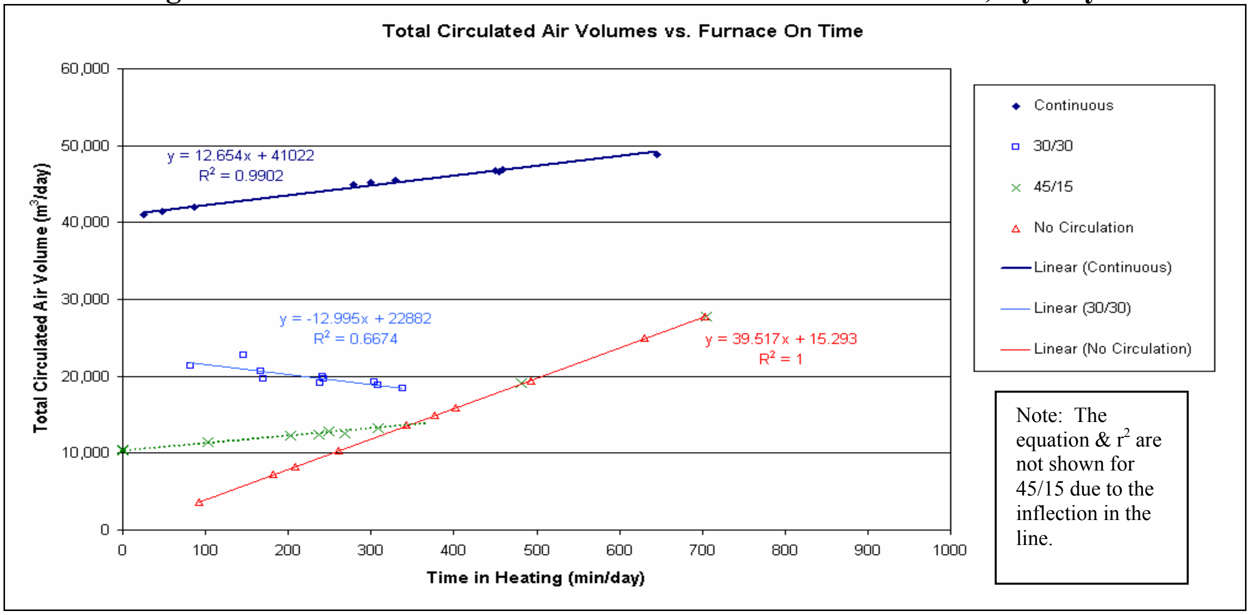


Figure 2. Furnace Fan Electrical Use

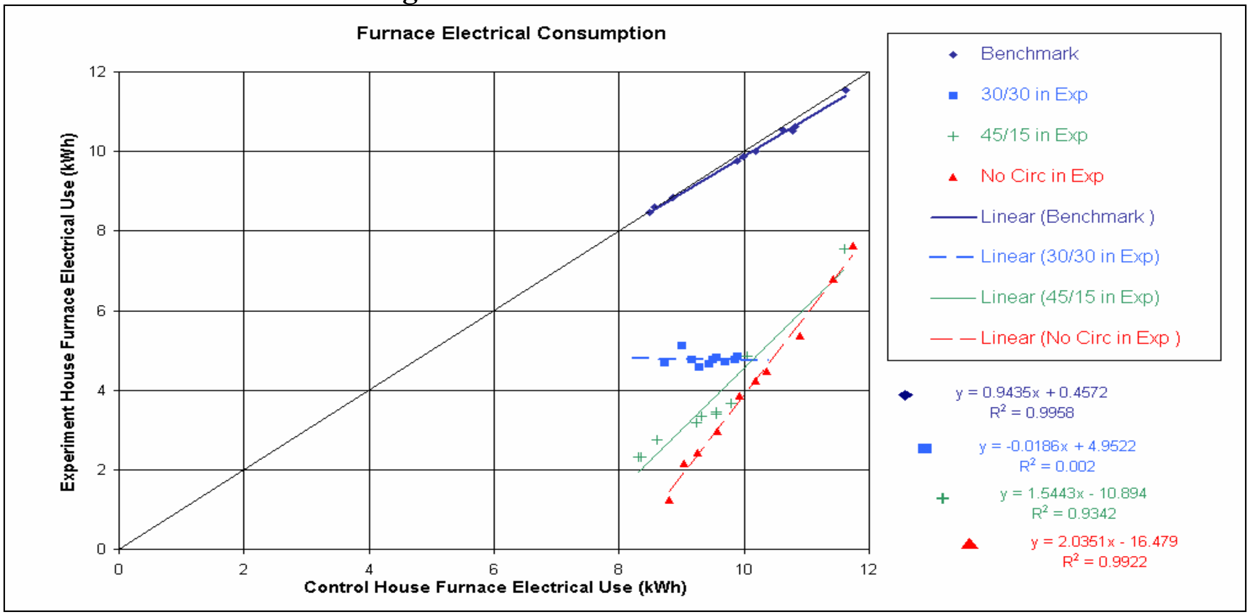


Figure 1 shows the total circulated air volume in the experimental house plotted against furnace on-times for each day of the experiment. The relationships appear to be linear and well correlated. The *45/15* points seem to fall on one of two straight lines. The highest two points are exactly on the no circulation line, and the remainder form a shallower line from there to the Y-axis. This inflection in the *45/15* line, and the shallow slope of the *30/30* line are discussed below. Thus, Figure 1 shows that on a daily basis, the effects of the programmable fan controller are regular, but the slopes and inflections of the lines require some explanation.

Furnace Electrical Use

Figure 2 shows the amounts of electricity used by the furnace in both houses for each circulation mode. Each point represents one day, with the amount used in the control house being the X-coordinate, and the amount in the experimental house as the Y-coordinate. The benchmark points show the results with *continuous circulation* in both houses, and since the amounts in each house are nearly equal, the points are all close to the 1:1 line. The other series represent the days when one of the other circulation modes was in effect in the experimental house. The points for the *30/30* mode show significant electrical savings in that house, and form a nearly horizontal line. The points for *no circulation* in the experimental house form a steep line. Above approximately 10 kWh/day in the control house, the *45/15* points seem to converge with the no circulation line, as they do in Figure 1. (Note the *45/15* point at the right end of the *30/30* line). All of the points for non-continuous circulation are well below those for *continuous circulation*, and show the potential for saving electricity with the fan controller.

Furnace Natural Gas

Most or all of the electrical energy used by the furnace should be converted into space heat. Thus, more electricity use by the furnace should mean less natural gas use. Conversely, modes that use less electricity should require more gas. Figure 3 shows the amounts of natural gas used by the furnaces in both CCHT houses during this project. As in Figure 2, each point represents one day, with the control and experimental houses on the X- and Y-axes, respectively.

As expected, the non-continuous modes do use more gas, but the increases are not exactly in accordance with changes in electrical use, as the *45/15* mode has the largest increases. The fact that the increases don't correspond exactly with the changes in furnace electricity use could be due to four factors: the 5% difference in gas use in benchmarking, the relatively small differences in the furnace electricity use, the small number of data points for each mode, and the fact that the *30/30* and *45/15* points should converge with the *no circulation* points, as shown below. Table 2 shows the average values for daily furnace electricity and natural gas use in each house by mode, and the differences between them. For electricity, the differences are clear and in the expected order, and the difference between benchmarking and *no circulation* is large: 7.46 kWh/day or 85%. On the other hand, the differences between *45/15* and *no circulation* is smaller: 1.88 kWh/day or 27%, and the difference between *45/15* and *30/30* is even smaller: 1.06 kWh/day or 10%.

Figure 3. Furnace Natural Gas Use

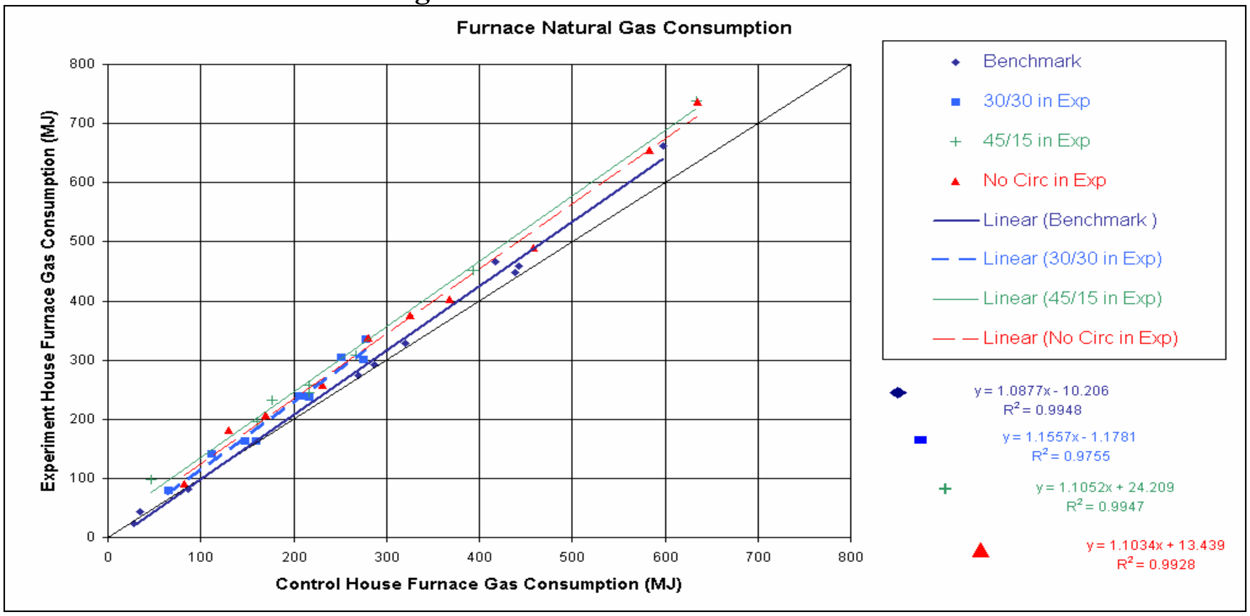


Table 2. Furnace Electrical and Natural Gas Use

	Control	Experimental	Difference
Furnace Electricity (kWh/day)			
Benchmark	9.98	9.87	0.11 (1%)
30/30 in Exp	9.41	4.78	4.63 (49%)
45/15 in Exp	9.72	4.03	5.69 (59%)
No circulation in Exp	8.81	1.24	7.57 (86%)
Furnace Natural Gas (MJ/day)			
Benchmark	292.4	307.9	-15.5 (-5%)
30/30 in Exp	192.1	220.8	-28.7 (-15%)
45/15 in Exp	264.0	316.0	-52.0 (-20%)
No Circulation in Exp	326.3	373.5	-47.2 (-14%)

Temperatures, CO_2 Levels & Circulation

Temperature data were analyzed in three ways, and none showed any significant differences due to circulation modes. CO_2 data was limited by problems with the release system and the sensors. The main effect of these problems is that there is only one day of *continuous circulation* with equal release of CO_2 in both houses and functioning sensors. Nevertheless, the results appear to be useful.

Table 3 shows the number of five-minute data points with master bedroom CO_2 levels above 1,000 ppm in the two houses, and the difference between them. On the single day of *continuous circulation*, the levels never went above 1,000 ppm. (The maximum levels were 972 ppm in the experimental house, and 922 ppm in the control). Thus, there is essentially no difference between the houses in *continuous circulation*. In *30/30* the difference is 26.4%, in *45/15* it is 284%, and in *no circulation* it is 180%. These results are consistent with the average volumes of circulated air. The fact that the CO_2 levels exceed 1,000 ppm 23% of the time in *no*

Table 3. Numbers of Data Points Above 1,000 ppm in the Two Houses, and Differences Between Them

Condition in Experimental House	# of Data Points	Data Points > 1000 ppm				Difference	
		Experiment		Control			
		#	%	#	%	#	%
Continuous Circulation	288	0	0.0%	0	0.0%	0	0.0%
30/30	2016	226	11.2%	179	8.9%	47	26.3%
45/15	2868	1557	54.3%	405	14.1%	1152	284%
No Circulation	2880	666	23.1%	238	8.3%	428	180%

circulation, and 54% of the time in *45/15 may* indicate that circulation in those modes is inadequate.

Average and maximum CO_2 levels in the master bedroom, and differences between levels in the master bedrooms and other locations were analyzed and also showed results consistent with the average volumes of circulated air. The maximum levels recorded in the master bedroom were 1450 ppm in *30/30* mode, 1634 ppm in *45/15*, and 1662 ppm in *no circulation*. Occasional levels above 1000 ppm are common in Canadian houses, and do not appear to cause harm or discomfort to the occupants.

Modeling, Comparisons and Projections

Furnace electricity and gas use with a programmable controller were modeled and compared with the measured results. The model answers some of the questions raised by the measured results, and was used to predict results for an entire heating season, a shoulder season and mid-winter. The model is based on hourly measured furnace on-times in one of the CCHT houses in Ottawa, which has 4673 heating degree-days (base 18°C) and a design heating temperature of -24°C (-13°F).

Modeling Furnace Electricity & Natural Gas Use

Figure 4 shows the general form for furnace electrical use with and without a programmable fan controller. The down-pointing arrows represent the amount of energy that can be saved on a given day by changing from continuous circulation to use of a fan controller. Since furnaces seldom if ever run for 24 hours/day, there will be savings on almost any given day. The up-pointing arrows represent the extra energy that the fan controller causes to be used to provide better circulation, compared with the no circulation case. Little or no extra energy should be required until the "shoulder season," when the furnace runs infrequently, and extra circulation may be required for good circulation and indoor air quality. For any fan controller program, its line will intersect with the no circulation line at some point, and will then coincide with the latter for higher furnace on-times. This point will occur at higher values of both furnace on-time and fan electricity for modes with shorter maximum off-times, e.g., for *30/30* as compared with *45/15*. For circulation modes with short maximum off-times, the fan controller line will start high on the Y-axis, and will have a nearly flat (perhaps even negative) slope. For modes with longer maximum off-times, the line will start lower, and have a positive slope.

Figure 5 shows the results of modeled furnace natural gas use. The difference between the benchmark (*continuous circulation* in both houses) and the other modes is clear, but the lines for the non-continuous circulation modes are very close, and those for *45/15* and *30/30* converge

Figure 4. General Form of Furnace Electrical Use with a Fan Controller

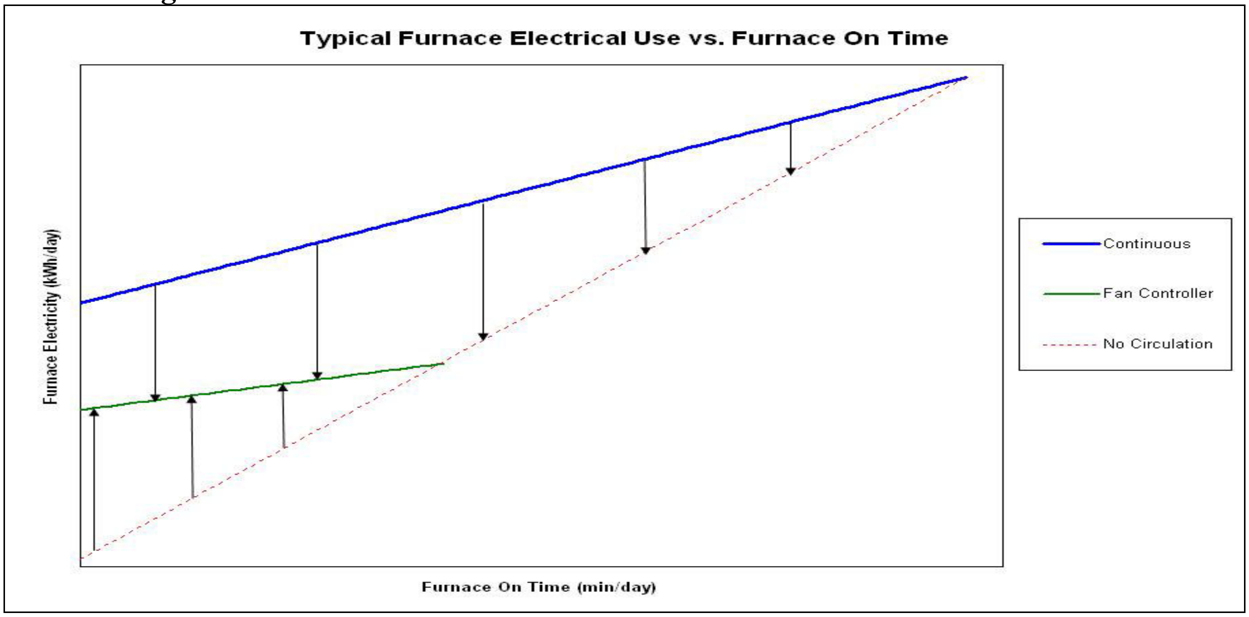
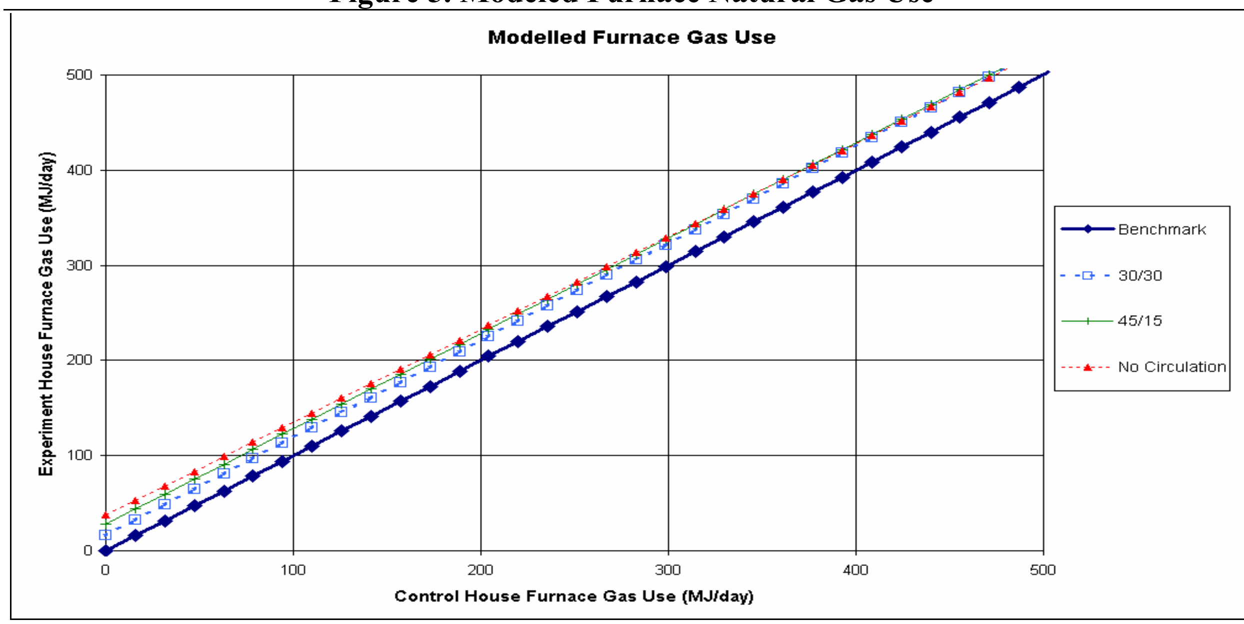


Figure 5. Modeled Furnace Natural Gas Use



with the no circulation line above 455 and 574 MJ/day, respectively. (Note that the ranges of Figure 5 are smaller than those of Figure 3 in order to show the details of gas consumption below the convergence points). For these reasons, it is not surprising that the measured furnace gas uses for the different modes are not very distinct nor in the expected order.

Modeling Seasons

Table 4 shows the simulated results for an entire heating season, and for a "shoulder season" (October). The first set of columns are for the heating season. These values change regularly in the expected way, i.e., daily circulated volumes and fan electricity decrease for circulation modes with longer maximum off-times. This is to be expected since all modes were modeled for the same days, while the irregularities in the earlier tables were due to the different amounts of heating time in the various modes. The differences in daily circulated volume between *continuous circulation* and the other three modes are large, while the differences among the other three modes are smaller. Since there are days with no demand for heat, there are days in which the *no circulation* mode results in no air being circulated within the house. These days generally occur during the shoulder season with the lowest ventilation rates, so the no circulation mode could well result in poor indoor air quality on those days.

The second set of columns in Table 4 show the results for the shoulder season. For no circulation, the minimum circulated volume is zero, and the mean is less than half its value for the heating season. For the other modes, the minimum and mean values are very close to their heating season values, indicating that the programmable fan controller maintains even amounts of circulation through the critical shoulder season. Simulations for mid-winter (January) confirm that result. For the entire 243 day heating season, switching from continuous to *30/30* circulation should save 1,117 kWh (49%) of furnace electricity, while increasing furnace gas consumption by 139 m^3 (7.6%). For a switch from continuous to *45/15*, the results should be saving 1,488 kWh (65%), while using an additional 173 m^3 (10.1%).

Table 4. Seasonal Simulation

	Heating Season				Shoulder Season			
	Cont. Circ.	**30/30**	**45/15**	**No Circ.**	**Cont. Circ.**	**30/30**	**45/15**	**No Circ.**
Daily Circulated Volume (m^3)								
Minimum	41,990	17,249	10,408	0	41,990	20,153	10,408	0
Mean	44,052	20,402	12,544	7,888	42,779	21,887	11,097	3,020
Maximum	47,773	22,881	22,122	22,122	44,157	22,881	12,300	8,289
Mean Furnace Electricity (kWh/day)	9.40	4.80	3.28	2.37	8.78	4.72	2.63	1.06

Summary & Conclusions

Programmable fan controllers are an inexpensive, practical way of providing existing new houses with variable amounts of air circulation. Fan controllers provide some of the benefits of energy-efficient furnace motors, and are easy to use with existing furnaces, while retrofitting motors is expensive and problematic.

Without a controller, the fan in most forced-air furnaces operates in one of two modes: only when there is a demand for space heat or cooling, or continuously. These two modes can be called *no circulation* and *continuous circulation*. The fan controller allows for intermediate modes. Compared with *no circulation*, the intermediate circulation modes provide significantly increased circulation of air through the house, especially during the critical shoulder seasons. Compared with *continuous circulation*, they continue to supply some circulation while saving significant amounts of electricity, and increasing the use of natural gas. The controller was not tested during air conditioning, but one would expect it to produce proportionately larger savings of electricity with no increase in gas use.

During controller testing, temperatures and carbon dioxide levels were analyzed for indications of inadequate circulation. The analysis of temperatures showed no such indications in any mode. Compared with continuous circulation, the maximum CO_2 levels with the fan controller were higher, and they exceeded the ASHRAE guideline of 1,000 ppm more often. However, they never exceeded (or even got close to) the Health Canada limit of 3,500 ppm at which human health may be affected, and they are not high compared to levels previously observed in a variety of Canadian houses. They may be associated with odors, or with high levels of humidity that could cause condensation or mould growth. But those conditions are easily observed and dealt with by occupants.

The available evidence suggests that most houses operate in *no circulation*. One survey (Philips 1997) showed that in Quebec about 50% of households operated their fans continuously, while in the rest of Canada only 20% did. This was confirmed by a more recent study in Manitoba (Proskiw 2002).

For households that now operate in *no circulation* mode and would like to have better circulation, a programmable fan controller can be recommended without reservation. The controller will provide better circulation, use more electricity and save some natural gas. The net effect will be a slight increase in total utility bills. For households that currently use continuous circulation and would like to save electricity while still providing some circulation, installation of a fan controller could be accompanied by some basic information on potential RH and mould problems, and how to deal with them. The controller will provide more even circulation, and will use less electricity and more gas, resulting in a net decrease in utility bills.

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