White paper on the comparative energy efficiency of zoned electric heaters
Convectair, Inc. / Convectair-NMT Inc.
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Contents :

Summary

While gas furnaces and heat pumps can be rated at various levels of energy efficiency, natural convection and radiant electric resistance heaters are all considered to be 100% efficient by design. All electric resistance heaters are therefore considered to be equal in terms of heating costs.

However, when asked to choose between a baseboard and, say, a clothes iron of equal wattage to heat a room, most people would intuitively choose the baseboard. If both are 100% efficient, why can't both heat the room for the same cost? Isn't it conceivable that design variations between different electric heaters could affect their operating costs?

Applying rigorous measurement standards and imaging systems, we can demonstrate that the use of most currently available electric heaters does in fact generate an increase in heat losses, resulting in unnecessarily high operating costs.

This research has led to the development of a family of wall-mounted natural convection heaters with close to true 100% efficiency, resulting in seasonal economies of 20% compared to baseboard heaters equipped with mechanical thermostats. These savings originate from a more even distribution of heat in the heated space, combined with more precise and more consistent temperature control.

As with any heating system, additional savings can be achieved by the use of temperature setbacks. Such additional savings vary depending on local climate conditions and setback schedules.

All these performance advantages can be demonstrated using the basic principles of heating combined with an understanding of the concept of design temperatures and temperature differences.

1. Introduction

The operating efficiency of a heating appliance is calculated by comparing the quantity of usable heat (BTU or KWh) generated by the system to the amount of energy contained in the fuel it consumes (cu.ft. of natural gas, gallons of LPG or fuel oil, KWh of electricity).

> Examples :
>
> A natural gas furnace consumes 98 cu.ft. of natural gas for one hour and provides 80,000 BTU of warm air in a home. Assuming that the average energy content of one cu.ft. of natural gas is 1,026 BTU (see note 1), this furnace has consumed 100,540 BTU of gas to produce 80,000 BTU of heat. Its efficiency is :
>
> 80,000 / 100,540 = .796 or 79.6%.
>
> An electric furnace consumes 18 KWh of electricity to run for one hour. It produces 61,420 BTU of warm air in a home. Since 1 KWh is equivalent to 3,412 BTU, the efficiency of that furnace is :
>
> 61,420 / 61,420 = 100%
>
> A geothermal heat pump consumes 7.6 KWh of electricity to produce 78,000 BTU of warm air. Using the same conversion rate from KWh to BTU, its efficiency is :
>
> 78,000 / 25,930 = 301%

In cases #1 and 3, the examples given, while typical, do not mean that all gas furnaces, or all heat pumps, have the same efficiency. Various designs generate different efficiencies. Manufacturers therefore advertise specific efficiency ratings for each model.

On the other hand, the process of transforming electrical energy into heat that is used by furnace #2 above (resistance heating) is governed by the laws of electricity that state that when an electrical current passes through a resistance, all the energy that is absorbed by the resistor is converted into heat. This process is 100% efficient.

In the following pages, we will demonstrate that although electric resistance heating is 100% efficient at the source (100% of the electrical energy is converted into heat), the design of heaters such as baseboards and some fan heaters create hot spots in a room, resulting in wasted energy and unnecessarily high heating costs. We will also describe how better designed convection heaters can avoid this problem.

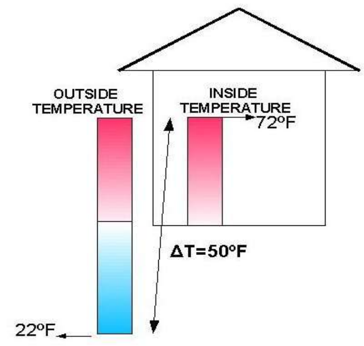
Combining such designs with a high performance electronic thermostat also avoids costly temperature swings and droop common to standard heaters.

Convectair's expertise in electric heating is the result of more than 30 years of field experience in Europe and North America, combined with extensive and rigorous laboratory testing. Some of these performance measurements and visualization tools are described here.

2. Fundamentals of heating

Heat always flows from a warmer place or object to a colder one. This flow of heat will continue until the two reach the same temperature (one object will cool down while the other will warm up).

The amount of heat flowing between the two is proportional to the temperature difference (*delta T* or ΔT) between the two bodies.



In the case of a structure located in a cold climate, heat will flow outward through the building envelope until the air inside the house reaches the temperature of the air outside. The amount of this heat loss is proportional to the ΔT between the inside and the outside : the greater the temperature difference, the greater the amount of heat flowing outward.

The role of a heating system is to replace the heat flowing out of the house. If the heating system is properly sized, it should be able to exactly compensate for the heat loss and allow a constant temperature to be maintained in the house. Since that amount varies depending on the ΔT, the sizing of heating system must take into account the coldest temperature for the house location, called the "outside design temperature" (see note 2).

Combining insulation factors with the local design temperature allows one to calculate the heat loss of a house in a specific location (see note 3).

Since heat loss is proportional to the ΔT, raising the interior temperature of a home has the same effect as lowering the outside temperature : if the outside temperature does not change (say 22˚F) and the interior temperature is raised from 72 to 77˚F, the ΔT would increase from 50 to 55˚F, a 10% increase. The amount of heat loss would increase by the same proportion.

An important consequence of that remark is that a small change in inside temperature may have a significant impact on heat loss, particularly in milder climates :

> Example :
> Heat loss impact of a 5-degree change in interior temperature (from 72˚F to 77˚F):
> –when the outside temperature is 22˚F : +10% (ΔT goes from 50 to 55˚F)
> –when the outside temperature is 47˚F : +20% (ΔT goes from 25 to 30˚F)

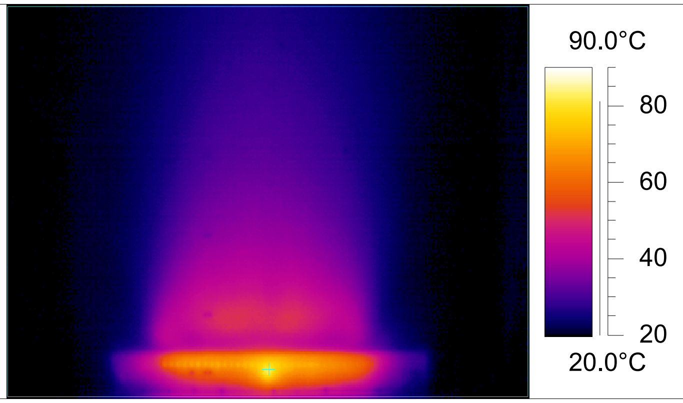
While this whole concept may appear counterintuitive at first, ask yourself how much sense it makes to lower your thermostat by a few degrees in Fairbanks, AK, when the outside temperature is -40˚F... Going from a setting of 72˚F to 68˚F represents a change of 4˚F over a ΔT of 112˚F, an increase of only 3.6% on your heating consumption.

This is not to say that you should overheat the house. It is just that the 4˚F setback will not have as visible an impact on your monthly cost as it would if you lived in Seattle's milder climate where the same 4˚F change would represent 10% of the ΔT on a 32˚F day (72-32=40, 4/40=10%), and therefore a 10% increase in your heating cost.

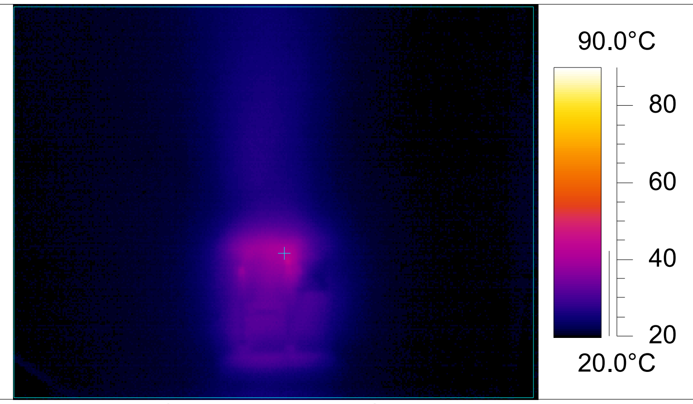
3. Temperature distribution in a room

If a room is left undisturbed (no presence in the room, no forced air flow), a natural convection current is created as heat is lost through the outside wall. As it loses heat, air along that wall cools down, gets heavier and falls to the floor. This cold air movement can be felt as a slight draft by someone seated next to a window. Traditionally, electric heaters have taken the shape of baseboards and are installed on cold walls and below windows in order to combat that cold draft. Alternatively, small fan-forced heaters are installed on opposite walls in order to blow warm air toward that cold wall.

In either case, a warm air current is created and rises along and against the outside wall and window. While it effectively counteracts the cold draft, this warm air current has the effect of warming the outside wall. Thermal imaging shows wall temperatures in excess of 100˚F over and behind a baseboard. Although the center of the room is maintained at the desired comfort level (68˚F in our lab), this concentration of heat increases the ΔT along the outside wall and therefore increases heat loss.



Baseboard 1000 W



Convectair MEZZO 7383 1000 W

Each image represents a wall area measuring 5 ft vertically from the floor by 6 ft 8 in wide. Both heaters were brought to their maximum operating temperature and then removed to expose the wall. The target mark (+) is placed on the hottest point of the wall. The average temperature is measured over the entire rectangle shown. The temperature scales are in degrees Celsius, where 20°C is equal to 68°F (ambient temperature in the testing room) and 90°C is equal to 176°F.

Unit	Min. Temp.	Max. Temp.	Avg. Temp.
1000 W baseboard	18.2°C (64.8°F)	82.5°C (180.5°F)	27.7°C (81.9°F)
MEZZO 1000 W	19°C (66.2°F)	44°C (111.2°F)	22.3°C (72.1°F)

Having measured that the average wall temperature is 9.8°F higher in the case of the baseboard, it is possible to calculate the increase in heat loss resulting from this uneven heat distribution. The percentage of the increase varies depending on outside conditions as described in section 5.

4. Thermostat performance standards

The most easily understood measurement of thermostat precision is the amount of swing that a thermostat allows in room temperature. Let's assume that a thermostat is set to 72˚F. As the heating system cycles on and off, the actual room temperature will rise and drop slightly. The difference between the highest and lowest resulting temperatures, as measured in the center of the room, is called amplitude. In the case of a baseboard controlled by a standard bimetallic thermostat, the amplitude can easily reach 8˚F. It typically gets worse as the thermostat gets older.

In certain jurisdictions, standards have been set to encourage the use of better quality thermostats. Seattle City Light (Seattle, WA) qualifies thermostats with a differential of 2˚F or better for preferential treatment. In France, established performance standards require the use of thermostats with an amplitude of 0.9˚F or better. High quality proportional action electronic thermostats such as the ones used in Convectair heaters have an amplitude of less than 0.2˚F.

How much is that worth in savings percentage? While the impact of thermostat amplitude on energy savings is not a simple one, it is known that people tend to choose to be a little bit too warm in order to avoid being a little bit too cold. In the case of thermostats with noticeable amplitude (>4˚F), this results in some users raising the thermostat setting and increasing energy use. An example is given in section 5, below.

Another aspect of thermostat performance has a substantial impact on energy consumption. It has to do with the ability of a thermostat to provide consistent temperature control over the entire operational range of a heater. The standard measurement is called thermostat droop and is calculated as follows :

> a) Using a room adjacent to a « cold climate » (a bi-climatic chamber), adjust the outside temperature and the heater thermostat to obtain a temperature of 68˚F in the middle of the room while the heater is cycling at 20% of capacity (on 20% of the time, off 80% of the time).
>
> b) Without changing the thermostat adjustment, lower the cold climate until the heater cycles at 80% of capacity and then measure the resulting temperature in the room.

The difference between the second temperature and the original 68˚F is called droop. It shows by how much the room temperature changed when the outside temperature dropped from a « mild » climate to a « cold » climate. There is no droop standard in North America. In France, thermostats are required to have less than 2.7˚F of droop. We measured standard bimetallic thermostats at about 5 to 8˚F of droop.

Large droop can increase the cost of home heating as shown in the next section.

Convectair thermostats have zero droop.

5. Impacts on heating costs

a) Impact of allowing warm air to rise along an outside wall :

In a baseboard-heated room, it is possible to calculate the increase in heat loss resulting from this uneven heat distribution by averaging the resulting wall temperatures over the surface of the outside wall and ceiling. The percentage of the increase in heat loss (and energy consumption) varies depending on outside conditions. In the following example, we use the temperatures observed in the laboratory comparisons of a baseboard and a Convectair heater illustrated above.

> If the average wall temperature is increased by 9.8˚F when using a baseboard instead of a Convectair heater, the increase in heat loss will be :
> - 40% when the outside temperature is 47˚F (ΔT going from 25 to 35˚F)
> - 25% when the temperature is 32˚F (ΔT going from 40 to 50˚F)
> - 20% when the outside temperature is 22˚F (ΔT going from 50 to 60˚F)
> - 12.5% when the outside temperature is -8˚F (ΔT going from 80 to 90˚F)
> - 10% when the outside temperature is -28˚F (ΔT going from 100 to 110˚F)

b) Impact of thermostat droop :

Thermostat droop can increase the cost of home heating : a conventional line voltage thermostat set at a comfort level when it is cold outside (in the evening, for example) will overheat when it becomes milder (the next day), unless someone is home to manually readjust it. This leads to unnecessary costs.

> As an example, if a thermostat overheats a home to 77˚F instead of 72˚F when the outside temperature is 32˚F (5˚F droop), heating energy consumption increases by 12.5% for the duration of that “overheat” period.

c) Impact of thermostat amplitude :

Using the same calculations as before, raising the thermostat by 3˚F from 72 to 75 (which is the case in parts of our office which are heated by a not very consistent rooftop system), will increase heating costs by 7.5% when the outside temperature is 32˚F.

Note that after extensive and rigorous studies, Hydro-Quebec, the second largest Canadian electric utility, launched a thermostat replacement program claiming 10-12% savings in annual heating costs when mechanical line voltage thermostats are replaced by proportional action electronic thermostats. Other electronic thermostat manufacturers claim even larger savings although no substantive proof is offered.

6. Laboratory evidence

a) Amplitude and droop comparisons

Tests were conducted under independent supervision to measure the performance of Convectair heaters compared to baseboards with mechanical thermostats.

Details of these tests are available from Convectair. The results were as follows :

	Convectair	***Baseboards***
Amplitude (measured at the center of the room)	0.2^{o}F	6^{o}F
Droop	-0.2^{o}F	8.1^{o}F
Energy consumption*	1.461 KWh (17% lower than baseboards)	1.758 KWh

*Note : total consumption over the final hour of each of three 12-hour test cycles for outside temperatures ranging between 28 and 50˚F.

In order to evaluate seasonal savings including the impact of droop, a calculation was made using average monthly temperature data in Montreal, QC, Canada, for the year 1982. The result showed savings of 22%.

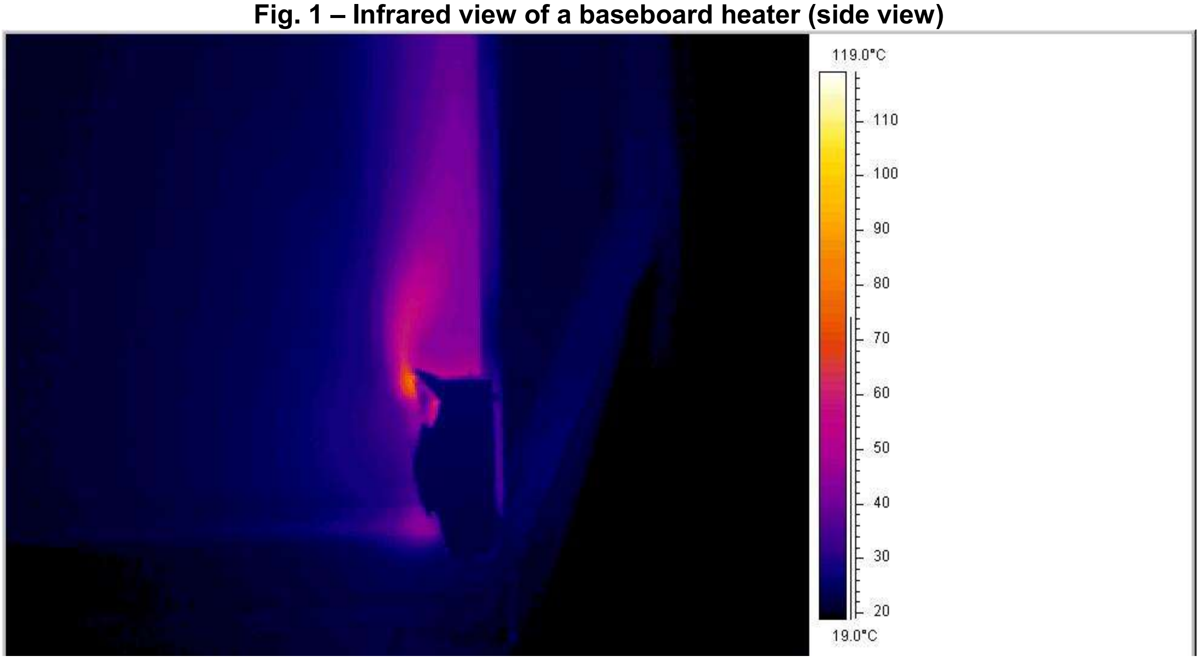
In addition, a specially built room allowing the visualization of air movement in a room with one exposed wall was used to compare the performance of various heaters.

The following infrared images show the heat flow as it comes out of a baseboard and a Convectair heater.

Note that the color temperature scale is in degrees Celsius where 20˚C is equal to 68˚F and 110˚C is equal to 230˚F .

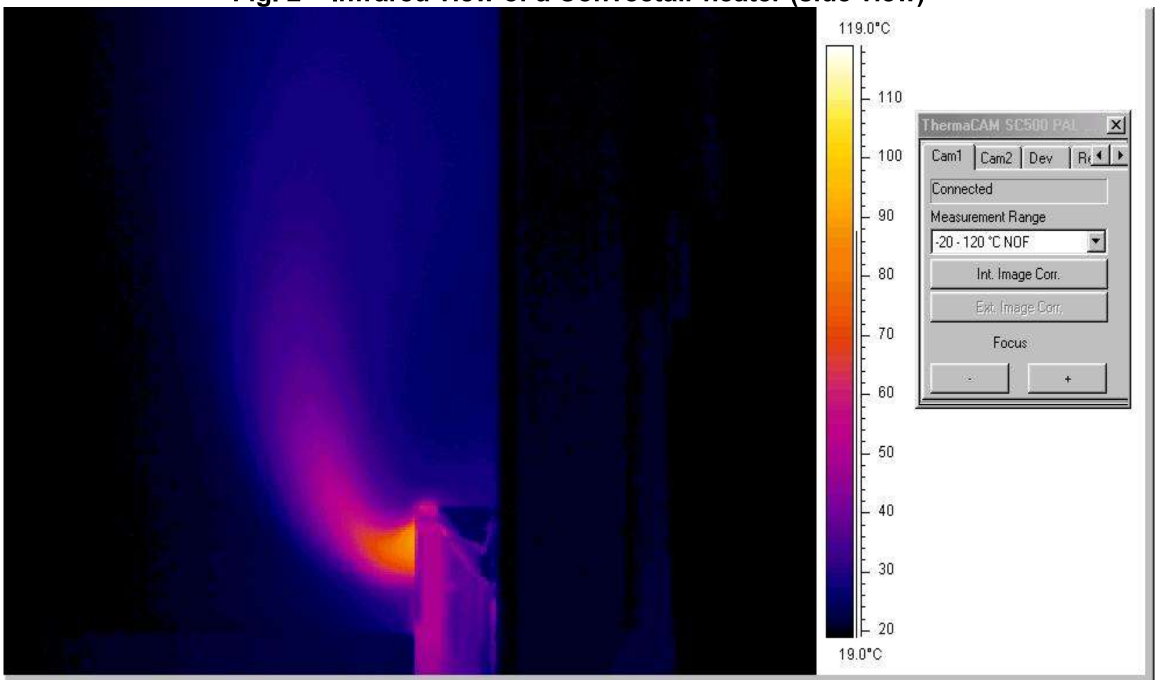
In the case of a baseboard, a very fast laminar air flow can be seen rising against the wall above the heater. This air flow then propagates in a turbulent movement along the ceiling to a depth of 12 inches for the entire length of the room with very limited air movement elsewhere.

Fig. 1 – Infrared view of a baseboard heater (side view)



In the case of a Convectair heater, a turbulent flow of warm air can be seen rising in front of the heater. This air flow draws air from the rest of the room generating a slow movement across the entire room.

Fig. 2 – Infrared view of a Convectair heater (side view)



The Convectair image shows that although there is a more intense flow of hot air at the outlet, the rising air flow cools down rapidly as it gets mixed with ambient air. No heat accumulates on the wall or the ceiling. In the case of the baseboard, the warm vertical air flow shows little mixing and heats the wall and the ceiling.

Temperature measurements show floor to ceiling temperature differences of less than 3˚F in the case of the Convectair heater and of more than 6˚F in the case of a baseboard.

7. Conclusion

While heating system operating efficiencies are an important factor in evaluating different home comfort solutions, true heating costs also depend on the ability of a heater to evenly distribute and control the heat it produces.

Heat loss calculations are the basis for designing an effective system. Those calculations assume a uniformly distributed interior temperature of 72˚F. In fact many heating systems tend to create warm spots along outside walls or ceilings, increasing heat loss. In the case of electric room by room heaters, this is especially true of baseboards, fan-forced heaters and cove heaters. Over the years, heating professionals have learned to “pad” their heat loss calculation to ensure that extra heating capacity can compensate for those additional heat losses.

The consequences are :

- higher load factors for the utility;
- higher heating costs and lack of consistent comfort for the customer (which, according to a 1999 Honeywell study is the #1 complaint of all home owners).

Convectair convection heaters are designed to provide more uniform temperature distribution and constant comfort. Avoiding warm spots on outside walls while eliminating thermostat swing and droop reduce seasonal heating costs by approximately 20% on average compared to baseboards heaters using mechanical thermostats.

Further savings can be obtained by the addition of an automatic setback system, such as the Convectair Programmer System which allows room by room setback of 4 to 13˚F, on a 24-h / 7-day customized schedule.

Notes :

1) *The energy content of natural gas may vary. If natural gas is invoiced by units of volume (ccf, Mcf or cubic meters), the utility must commit to a minimum energy content for the gas that it delivers to its customers. This energy content would normally appear in the tariff description of that utility. The calculations above assume that the customer effectively receives the agreed energy content. Any lowering of that energy content would result in additional energy costs.*

2) *In order to size a heating system, we perform a “heat loss calculation”. In addition to the insulation value of each component of the building's envelope and prescribed infiltration rates, this calculation takes into account the difference (ΔT) between the “Inside Design Temperature” (usually taken as 72˚F) and the “Outside Design Temperature” for the location. For any given location, this temperature is such that there is only a 2.5% probability that the weather will be colder (based on 30 years of temperature data). Outdoor design temperatures for many locations are published in the ASHREA handbook (US) or by the Canadian Standard Association (CSA Standard C173-1).*

3) *Reference tables provide conductivity factors for most common materials and wall systems. These factors are expressed in BTU/h (or in watts) per square foot, per 100˚F of ΔT. For example, an R-19 wall (glass wool insulation placed in a 2 x 6 wall structure, with gyprock walls over a plastic vapor barrier inside, a rigid wind barrier covered by clapboard on the outside) has a typical conductivity of 5.1 BTU/h per square foot per 100˚F of ΔT (1.5 watts).*