FEATURES

Sensor-Based Smart Air Convector

Alexander built a sensor-based "smart" air convector that provides efficient heat transfer from an electric board heater or a water/steam-based heater. Although the convector works in conjunction with a room thermostat, no rewiring or any modification to the existing heating system is necessary.

By Alexander Pozhitkov

A cold season naturally means heavy use of the heating system. Many houses have either electric baseboard heaters or hot water/steam radiators. Strangely enough, such a heater can get extremely hot while the room it's in barely warm. (In fact, the dust in the scalding hot heater nearly always turns carbonized black!) In addition, when the thermostat turns the baseboard heater on and off, the heater produces annoying crackling noise, which is often quite loud in the case of old heaters. The most obvious reason for such a misfortune is inadequate air convection that is generated by the radiators that prevents efficient heat transfer from the heater into the room.

Baseboard heaters and hot water/steam radiators rely solely on air convection as a mode of heat transfer. On one hand, such heating systems have a clear advantage over the forced air heating systems, because the latter require difficult installation of air ducts and are often noisy due to the fans moving air. The disadvantage of the non-forced (natural) air convection system is that the hot air streams are likely to form around the heater a laminar flow, which has a thick layer of stagnation. The layer of stagnant flow acts as a blanket surrounding the heating element therefore greatly diminishing the temperature differential at the surface of the heating element. This situation results in a much lower heat transfer coefficient than that of the forced flow.

The heat transfer coefficient is a factor relating the temperature differential with the heat transfer rate according to the Newton's cooling law. The higher the coefficient, the more efficiently the heat is being transferred from the heater into the environment (i.e., the room):

$$hA\Delta T = \frac{dQ}{dt}$$

h is the heat transfer coefficient. A is the area of the heater. Q is heat. t is time. ΔT is the temperature differential between the environment and the heater. At this moment, this equation is too abstract to be useful, because it does not include the power of the heater and its temperature. We will return to the analysis of this equation with concrete values in the second part of the article when I the system to test.

PHOTO 1
This is the air convector installed under the electric baseboard heater.

There is another complicating factor. The baseboard and hot water/steam heaters are screened with a solid metallic sheet preventing the room inhabitants from burns. The space formed by the room's wall and the screen acts as a "chimney" providing a pressure differential potentially improving the convection by adding the draft. Unfortunately, the small height of the baseboard heater does not provide enough air pressure difference for creating an adequate draft.

Here we propose a system called "smart air convector" that is in synch with the heater. Importantly, the system requires no modification to the existing thermostat and wiring! The room thermostat is doing its job by turning the heater on and off depending on its setting. The convector turns on when it senses the heater is getting hot and turns off when the heater is cooled down sufficiently, thereby efficiently drawing the heat off the unit and delivering it to the room. Also, the forced air convection evens out the temperature profile within the heater thus notably reducing the crackling noise.

THE SOLUTION

Photo 1 shows the overall look of the convector. Ten PC fans are fixed onto a wooden frame, which is situated under or leaned toward the heater. Since the goal of the system is to be efficient in all senses, we also considered using recycled materials. It is amazing how much of still useable computer junk is available elsewhere. Here in the Seattle area there are several stores offering recycled PC parts. Naturally, we obtained the PC fans for our smart convector from the PC recycle store for a couple of dollars apiece. The electronic part of the convector is powered by a 12-V power supply, which was also procured from a PC recycle store for $1.

When the smart air convector is activated, the fans blow air underneath the baseboard heater. The heated air flows from the upper opening of the heater. This system works equally well with electric and water/steam-based heaters.

A temperature sensor is inserted between the radiator plates to trigger the air convector on or off (see **Photo 2**). Temperature sensing enables the convector to work with nonelectric heaters as well as alleviates the need to modify the wiring of the electric heaters. **Photo 3** shows a closer look at the temperature-sensing unit, which is made of the Texas Instruments LM35DZ integrated circuit (precision temperature sensor), whose plastic TO-92 case is inserted into 1/4" ID copper pipe. The copper pipe provides protection for the temperature sensor as well as the way to average out the temperature profile of the heater's heating element. One end of the copper pipe is squeezed with pliers. Three wires connected to the LM35DZ come out of the other end. The insulation of the wires is rated for temperature above 250°F (120°C). The wires encased with a braided metallic shield, which in turn is enclosed into a heat-resistant fiberglass-polymer sleeve. A heat-shrink piece of tubing (white in Photo 3) is holding together the copper pipe, the cable shield and the heat-resistant sleeve. It is important to note that the braided

PHOTO 2
The temperature-sensing unit is inserted between the radiator plates.

PHOTO 3
This is the temperature-sensing unit. The LM35DZ temperature sensor is inside the copper pipe.

metallic shield is placed over the pipe such that the shield and the pipe are electrically connected. Since the pipe is in direct contact with the heating element through the braided metallic shield, the control circuit has the same potential as the heating element. This arrangement makes the control unit highly resistant to the electric noise.

The control circuit is built around the comparator LM393N (see **Figure 1**). Resistors R3, R4, and R7 determine hysteresis for the comparator, which make the relay to turn on at approximately 140°F (60°C) and turn off at 99°F (36°C). The hysteresis improves stability of the convector and makes sure all heat is extracted after the room thermostat turns the heater off. The output of the comparator controls power MOSFET IRLU024N (Q1) via the divider R5 and R6. This particular FET used in our design switches on at TTL levels, hence the divider is necessary. Diode D1 establishes reference voltage on the negative input of the comparator. Resistor R2 is critical for the correct operation of the temperature sensor.

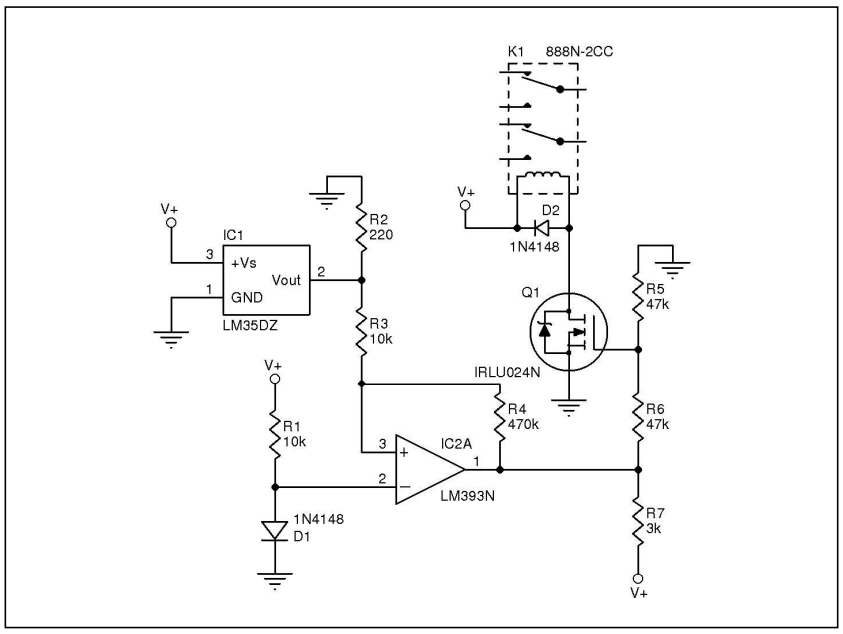

FIGURE 1
This is the convector control circuit. Relay K1 turns on at approximately 140°F (60°C) and turns off at 99°F (36°C). V+ = 12 V.

Without the R2, the temperature sensor was found to produce voltages incoherent with the measured temperature.

It is worth explaining how the hysteresis is established. An equivalent circuit is shown on **Figure 2**. Given that R4>>R3, when the switch is closed, which is the same as LOW on the open collector output of the comparator, the voltage U is determined by the temperature sensor, hence U = V_{SENS}. Therefore, this voltage is proportional to the sensed temperature when the comparator's output is LOW. As the heater's temperature increases, the U reaches above the threshold determined by R1 and D1 (600 mV) and the comparator's output goes HIGH (i.e., the switch is open on the equivalent scheme). The voltage U is then determined by the following formula (with R4>>R7):

$$U = \frac{(V_+ - V_{SENS})R_3}{(R_7 + R_4 + R_3)} + V_{SENS} = \frac{V_+ R_3 + V_{SENS} R_4}{R_4 + R_3}$$

Now on the cooling down phase, the heater's temperature decreases and V_{SENS} will have to drop down to 360 mV to make U = 600 mV**.** Therefore, the turn off temperature of the fans is lower than the turn on temperature.

CONSTRUCTION

Figure 3 shows the convector's circuitry (with dimensions). The convector's frame is made of two spruce pine furring strips 0.75" × 1.5" × 96" that were cut to appropriate lengths. The long sides of the frame are held together by four short pieces made from the same strips fastened with wood screws and metal brackets. Ten PC fans are evenly spaced along the length of the convector to create a smooth wide airflow**.** The circuit board is housed in a small plastic box (the black block on the left side in both Photo 1 and Figure 3). Fans are connected in parallel; their wires run in a cable canal towards the box with the circuit board. The cable channel can be seen on Photo 1 as a white tube on the bottom of the convector.

USE & MEASUREMENTS

The convector has been in heavy use for three years. In Seattle, the cool season begins from late September and lasts until early May. The convector had only one failure at the temperature-sensing unit. The reason for the failure was quite interesting. Initially, we thought that adding a thermo-conductive paste inside the copper tube would improve the sensitivity of the unit. It turned out that the paste destroyed insulation of the wires

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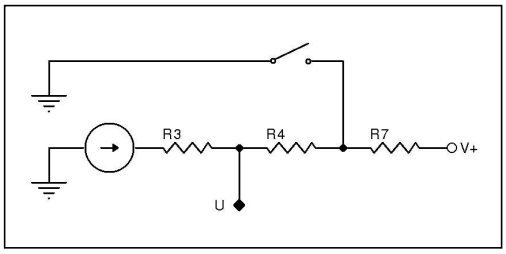

FIGURE 2
An equivalent circuit establishing hysteresis

and they shorted. For the next generation of the temperature sensing unit, we avoided the thermo-conductive paste altogether. The performance did not change at all!

Subjectively, the environment in room with the functioning smart convector is much more pleasant than without. It feels warmer. The temperature fluctuations between the ON and OFF cycles of the baseboard heater are not noticeable. The fans run very quietly. Their light hum actually helps to fall asleep! The crackling noise of the baseboard heater is nearly gone, so is the smell of burned dust.

It is interesting to conduct actual quantitative measurements to objectively assess the performance of the convector. We conducted the following experiment. Early morning, when the outside temperature was in the 40°F range, the room thermostat was set to 70°F. The door to the room was closed and an experimenter (the author of this article) was present all the time during the following measurements. Temperature of the heating element of the baseboard heater was measured with a thermocouple connected to a digital thermometer. The temperature measurements were recorded manually using Excel and for each measurement a timestamp was automatically assigned. Measurements were conducted between two audible clicks of the thermostat corresponding to turning the baseboard heater ON and OFF. Two regimes were tested: one run of measurements was conducted with the smart convector active and another run with the convector inactive.

Let us compare the time-temperature profiles of the two regimes. Figure 4 top shows the difference between the overall time-temperature profiles. Points B and C indicate the times when the heater is turned OFF by the thermostat. Apparently with the smart convector, the heater is ON longer! Specifically, when the smart convector is used, there is 26% more heat delivered to the room. It may sound paradoxical, why with the convector the heater ON time is longer. Nevertheless, it becomes clear when we consider that the hot air raising up from the heater forms irregularly shaped streams that eventually reach the thermostat and trigger it off. In the case of our room, the streams reached the thermostat prematurely before the room was adequately warmed up. (Note, it is also possible that depending on the location of the thermostat the streams would take longer to reach it, hence the room would overheat). Conversely, when the smart convector is used, all air in the room is mixed and the thermostat triggers only when the entire room reaches the desired temperature.

The temperature profiles shown in **Figure 4** contain more information worth analyzing. Point A indicates the moment when the smart convector turns on. Although the electronics was designed to turn smart convector ON at lower temperature than one can see at the point A, we believe there is a certain delay before the temperature of the sensor reaches the set threshold, while the temperature of the heater continues to increase. Note that the maximum temperature reached by the heating element is significantly lower when the smart convector is active compared to the case when the convector is inactive. Clearly, the lower temperature results in less expansion of the heater, hence less stress on the material and less crackling noise.

Between the points A and B there is a dynamic equilibrium manifesting itself as a flat part of the profile. Specifically, since the temperature of the heater does not change, the amount of heat produced by the electricity per second is equal to the amount removed by forced convection, dQ/dt = W, where W is the heater's power. This part of the profile enables us to calculate the actual value of the heat transfer coefficient multiplied by the area of the heater:

$$hA = \frac{W}{\Delta t}$$

W is 1,500 W. ΔT is 105.4°K. hA is 14.2 $JK^{-1}s^{-1}$. This value does not tell us yet if the smart

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Dr. Alexander Pozhitkov has an MS in Chemistry and a PhD in Genetics from Albertus Magnus University in Cologne, Germany. He is involved with interdisciplinary research relating to molecular biology, physical chemistry, software, and electrical engineering. Currently, Dr. Pozhitkov is a researcher at the University of Washington, Seattle. His technical interests include hardware programming, vacuum tubes, and high-voltage electronics.

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SOURCES

LM393N Comparator
Fairchild Semiconductor | www.fairchildsemi.com

LM35DZ Precision temperature sensor
Texas Instruments | www.ti.com

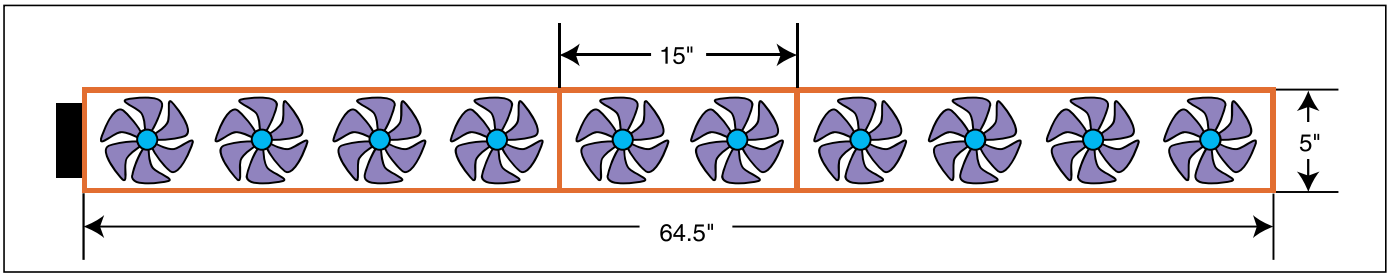

FIGURE 3
The dimensions of the smart air convector

convector is improving the heat transfer or not. The true indication of the improvement comes from the analysis of the cooling parts of the profiles (i.e., points B and C onwards). First, the Newton's cooling law has to be rewritten in terms of temperature and total heat capacity of the heating element, C, as follows:

$$\frac{dT(t)}{(dt)} = \frac{hA}{C}\Delta T$$

Solution:

$$T(t) - T_{ENV} = \left(T(0) - T_{ENV}\right)e^{-\frac{hA}{C}t}$$

Fitting exponents to the cooling profiles allows finding hA/C values for both cases when the smart convector is active and inactive. Since the values of A and C are constant, we find that the efficiency of heat transfer with active smart convector is approximately 1.6× (i.e., 0.019/0.012) times better than without.

Finally, from the dynamic equilibrium and the cooling parts of the temperature profile in the case of the active smart convector, we can calculate the total heat capacity of the heating element (although finding this value is just for curiosity): C = 14.2/0.019 = 747.4 JK^{-1}. If we assume that the heating element weighs approximately 2 kg, the specific heat capacity will be close to that of iron (449 $JK^{-1}kg^{-1}$), which certainly makes sense and indirectly validates our analysis.

EFFICIENCY

Natural air convection is not an effective way of heat transfer from a heater into the room. This ineffectiveness causes a heating element of the room heater to reach high temperatures, which results in significant expansion followed by shrinkage as the thermostat turns the heater on and off. The expansion causes stress on the materials and audible crackling noise. My maintenance-free "smart air convector" provides the advantage of forced air convection and features simplicity of construction, installation, and use. The system provides 1.6× higher efficiency of heat transfer compared to the standard baseboard heater without the smart air convector. The smart air convector also significantly reduces the temperature reached by the heating element, thus reducing the crackling noise and expansion-shrinking stress.

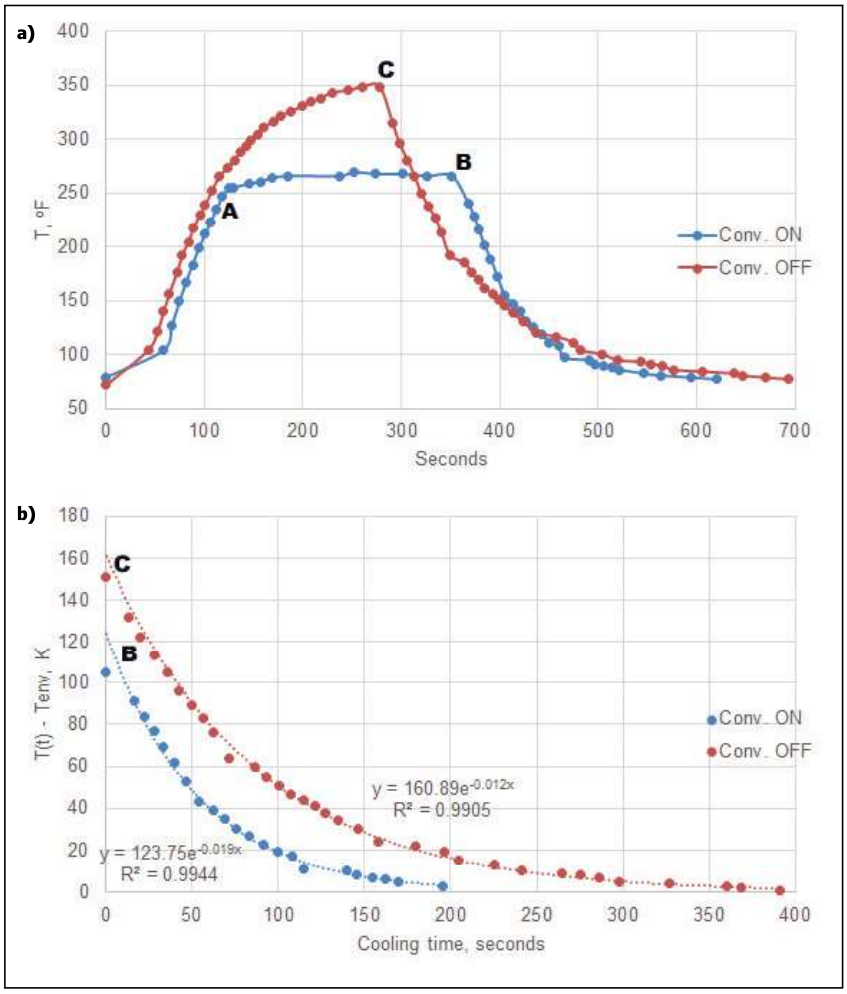

FIGURE 4
These are temperature-time profiles of the heating element corresponding to active and inactive smart convector. **a**—This is the overall profile. **b**—This is the cooling profile. Labels B and C mark corresponding points on both figures.