Sustainable HVAC Systems in Low-Energy Design in Commercial and Residential Buildings

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Abstract:
We present a novel method of building comfort control, focused around the occupant. Custom sensing, communication, and actuation hardware were developed to locate users in a building, and measure various parameters directly on the body. These signals were used to infer user comfort and control the air-conditioning system to direct air flow where it was needed, when it was needed. A three month study of the system was conducted, with four weeks of this experimental control strategy compared to the previous four weeks of standard control. An improvement in both comfort and energy usage are shown as a result of this user-centric control system.

I. INTRODUCTION
Creating an appropriate indoor climate is essential to worker productivity and personal happiness. It is also an area of large expenditure for building owners. The largest consumer of energy in the United States is buildings, with residential stock accounting for 21% and commercial stock accounting for 18%, combining to 39%. Within buildings themselves, the largest energy sinks are the heating, ventilation and air-conditioning (HVAC) systems. In residential applications, HVAC accounts for 26.1% of the total energy use, whereas in commercial applications, HVAC accounts for 53.4%. This makes building support systems, especially in the case of commercial buildings, a prime target for energy savings. But, what can be done to reduce costs in these areas? Either more efficient ventilation technologies can be developed or the existing technologies can be used more efficiently. Considering the long life span of buildings, and the fact that most commercial buildings are more than 15 years old, the latter proposition seems more cost effective, as merely adding a new control and sensing layer would be far less expensive than replacing a whole ventilation system. This idea is promoted further by the notion that most buildings are currently being run inefficiently due to the non-adaptable nature of their control systems, and that savings of up to 35% are possible. As Vastamaki et al. clearly describe in their analysis of thermostat usage, the fundamental efficiency of the building and the comfort of the occupants both suffer when the occupant does not understand the behavior of the building. Users are shown to consistently over-turn thermostat dials in response to uncomfortable conditions, causing thermal oscillations that waste energy and create an uncomfortable environment. Work to create such responsive environments began in earnest with the beginning of ubiquitous computing in the late 1980s. At Xerox PARC, offices were equipped with radio-frequency identification (RFID) and light, temperature, and occupancy sensors, which were allowed to turn off outlets, adjust HVAC systems, and control lighting. Portable devices allowed users to edit preferences wherever they were in the building. Little use a similar approach to resolve the conflicting comfort needs of users. These very programmatic responses were challenged by Mozer, whose neural networked house would purpose-fully turn lights off in order to understand if they were needed. Although this creates a longer learning curve than reassigned knowledge, it is capable of adapting over time without intentional user input. Adaptation has also been explored by modeling buildings as multi-agent systems. Ultimately, the majority of HVAC control work is focused on energy savings and temperature regulation, not human comfort. Although the control algorithms and adaptive strategies are directly applicable, the determination of personal comfort is not a solved problem. Multiple factors have been studied in their relationship to comfort, with the Predicted Mean Vote (PMV) being the most common metric. The PMV averages user comfort over large populations considering temperature, humidity, wind speed, thermal radiation, activity, and clothing. This works well in practice, but does not fit all needs. A variety of other factors influence comfort, including age, local climate and culture, and the availability of natural ventilation. The major use of the PMV is to set boundaries on temperature, humidity, and wind speed to a comfortable level within a building. Distributed sensor networks have been employed in attempts to assess comfort by measuring PMV values in real-time, but these involve cumbersome hardware, invasive systems, or have limited accuracy. These previous works, with the exception of, attempt to assess the PMV as a global variable: a fixed standard for all people. Megri et al. use PMV sensors similar to, and poll the user as does, but instead use a support vector machine algorithm to determine the indices of the occupant’s comfort, rather than using a PMV table. They show 99% accuracy at predicting comfort in this manner, which points to the possibilities of automatic recognition of comfort, on a person-by-person basis. Unfortunately this work involved large, tethered sensors which are required in three locations in close proximity to the user. The problem is not only one of assessing an individual’s personal comfort level - an effective control system must also be able to locate the person and affect that proximate temperature. As temperatures can vary greatly, even within the same room, this proves a difficult task. Forced air distribution systems, particularly under floor methods, can be targeted at points along the run to allow air to circulate locally. Many companies make systems [21] which implement this, usually under the name Task Ambient Conditioning (TAC). These systems allow the user to adjust air flow, and sometimes temperature, at a local vent. Not only is the availability of fresh air shown to give greater comfort, it is also more efficient, as air is only chilled where needed, and larger sections of the building can be allowed to

drift out of normal comfort zones. TAC systems are very expensive and difficult to install after initial construction, however. Our work addresses these problems by creating and testing at scale a uniquely adaptive control structure based upon both pre-assigned and dynamic knowledge. The user is only required to press a button indicating the direction of discomfort, if and when she is uncomfortable, and the building deals with the difficult tasks of dynamic energy management and conflict resolution. Specific sensor hardware is developed, which make the task of installing and operating these systems easier. Adaptive pattern recognition and control algorithms are presented, along with their efficacy in increasing the personal comfort of building occupants while reducing building energy consumption.

II. PRINCIPLE OF REFRIGERATION

When one hears the term air conditioning, usually the first thing that comes to mind is cold air. The mechanical refrigeration system demonstrates three basic laws of refrigeration which are the basic of all natural and mechanical refrigeration systems.

**Law 1:** Refrigerate is to remove heat. The absence of heat is cold. Heat is ever present. Law 1 is illustrated by the refrigeration system of automobile. Heat removed from the passenger compartment of the vehicle. In so doing, the temperature is lower. The absence of heat is cold. It if is now asked, “What is cold?” it appears that the answer is that cold is the absence of all heat. If it is true, at what point is all the heat removed from matter? Ice, at 32°F (0°C), is said to be cold. But solid carbon dioxide (CO2), or dry ice, is even colder at its normal temperature of -109.3°F (-165.8°C). Dry ice is so cold that if it is touched, one has the sensation of being burned. However, it cannot be said that dry ice is cold either because it still contains a large amount of heat as measured in Btu. Complete absence of heat does not occur until the temperature of -459.6°F (-273.16°C) is reached. All temperature above this value contains heat. For example -459°F still contain 0.67°F of heat; -273°C still contain 0.16°C of heat. In summary then, cold is the absence of heat energy. According to current scientific theory, absolute zero is the point at which all molecular movement stops. Since molecular movement causes heat energy, it follows that if there is no movement there is no heat.

**Law 2:** Heat is ready to flow or pass to anything that has less heat. Nothing can stop the flow of heat; it can only be slowed down. Law 2 is demonstrated by the special refrigerant in the evaporator. In this instance, heat is ready to flow to anything that contains less heat.

**Law 3:** If a change of state is to take place there must be a transfer of heat. If a liquid is to change to gas, it must take on heat. The heat is carried off in vapor. If a vapor is to change into a liquid it must give up heat. Law 3 is shown by the liquid refrigerant in the evaporator. That is, as the refrigerant takes on heat, it changes to vapor. The heat is carried off to be expelled outside the car.

**Conventional Air Conditioning System**

Usually what the air conditioning first brings to mind is cold air. Actually, an air-conditioning system automatically controls the temperature, humidity, purity, and circulation of air. In mobile vehicle air-conditioning system, air conditioning is a system that cools, dehumidifies, and circulation the air the air inside the driver and passenger compartment of a vehicle.
a general idea of a thermoelectric cooler's capabilities, it might be helpful to offer this example. If a typical single-stage thermoelectric module was placed on a heat sink that was maintained at room temperature and the module was then connected to a suitable battery or other DC power source, the "cold" side of the module would cool down to approximately -40°C. At this point, the module would be pumping almost no heat and would have reached its maximum rated "Delta T (DT)." If heat was gradually added to the module's cold side, the cold side temperature would increase progressively until it eventually equaled the heat sink temperature. At this point the TE cooler would have attained its maximum rated "heat pumping capacity" (Qmax). The Seebeck, Peltier, and Thomson Effects, together with several other phenomena, form the basis of functional thermoelectric modules. Without going into too much detail, we will examine some of these fundamental thermoelectric effects.

4.1 Seebeck Effect

In 1821 Thomas Johann Seebeck found that a circuit made from two dissimilar metals, with junctions at different temperatures would deflect a compass magnet. Seebeck initially believed this was due to magnetism induced by the temperature difference. However, it was quickly realized that it was an electrical current that is induced, which by Ampere's law deflects the magnet. More specifically, the temperature difference produces an electric potential (voltage) which can drive an electric current in a closed circuit. Today, this is known as the Seebeck effect. The voltage produced is proportional to the temperature difference between the two junctions. The proportionality constant is known as the Seebeck coefficient, and often referred to as the thermoelectric power or thermo power. The Seebeck voltage does not depend on the distribution of temperature along the metals between the junctions. This is the physical basis for a thermocouple, which is used often for temperature measurement.

\[ V = (\text{Th} - \text{Tc}) \]  

\[ \text{Vo} = \text{axy} (\text{Th} - \text{Tc}) \]  

Where, Vo is the output voltage in volts axy is the differential Seebeck coefficient between the two materials, x and y, in volts/oK Th and Tc are the hot and cold thermocouple temperatures, respectively, in oK.

4.2 Peltier Effect

In 1834, a French watchmaker and part time physicist, Jean Charles Athanase Peltier found that an electrical current would produce heating or cooling at the junction of two dissimilar metals. In 1838 Lenz showed that depending on the direction of current flow, heat could be either removed from a junction to freeze water into ice, or by reversing the current, heat can be generated to melt ice. The heat absorbed or created at the junction is proportional to the electrical current. The proportionality constant is known as the Peltier coefficient. If we modify our thermocouple circuit to obtain the configuration shown in fig, it will be possible to observe an opposite.

\[ \text{Qc} = \text{Qh} = \text{pxy} \times \text{I} \]  

Where, pxy is the differential Peltier coefficient between the two materials, x and y, in volts I is the electric current flow in amperes Qc, Qh is the rate of cooling and heating, respectively, in watts Joule heating, having a magnitude of I x R (where R is the electrical resistance), also occurs in the conductors as a result of current flow. This Joule heating effect acts in opposition to the Peltier effect and causes a net reduction of the available cooling.

4.3 Thomson Effect

Twenty years later, William Thomson (later Lord Kelvin) issued a comprehensive explanation of the Seebeck and Peltier Effects and described their interrelationship. The Seebeck and Peltier coefficients are related through thermodynamics. The Peltier coefficient is simply the Seebeck coefficient time's absolute temperature. This thermodynamic derivation leads Thomson to predict a third thermoelectric effect, now known as the Thomson effect. In the Thomson effect, heat is absorbed or produced when current flows in a material with a temperature gradient. The heat is proportional to both the electric current and the temperature gradient. The proportionality constant, known as the Thomson coefficient is related by thermodynamics to the Seebeck coefficient. When an electric current is passed through a conductor having a temperature gradient over its length, heat will be either absorbed by or expelled from the conductor. Whether heat is absorbed or expelled depends upon the direction of both the electric current and temperature gradient. This phenomenon,
known as the Thomson Effect, is of interest in respect to the principals involved but plays a negligible role in the operation of practical thermoelectric modules. For this reason, it is ignored.

Thermoelectric Materials
The thermoelectric semiconductor material most often used in today's TE coolers is an alloy of Bismuth Telluride that has been suitably doped to provide individual blocks or elements having distinct "N" and "P" characteristics. Thermoelectric materials most often are fabricated by either directional crystallization from a melt or pressed powder metallurgy. Each manufacturing method has its own particular advantage, but directionally grown materials are most common. In addition to Bismuth Telluride (Bi2Te3), there are other thermoelectric materials including Lead Telluride (PbTe), Silicon Germanium (SiGe), and Bismuth-Antimony (Bi-Sb) alloys that may be used in specific situations.

Characterization of Bi2Te3 And Sb2Te3 Films
A glass substrate was attached to the patterned wafer, so that a sample of the deposited film could be obtained for Seebeck coefficient, resistivity and thickness measurements, as well for x-ray diffraction analysis. A silicon substrate with a thin layer of platinum was also included to allow for stoichiometry analysis of the film cross-section. Energy dispersive x-ray analysis (EDX) was used to identify the elements present in the films, and their relative concentrations. The atomic ratio between Te and Bi (or Sb) varied up to ±10% along the film thickness. Note that these are qualitative values, i.e., they must be considered only for comparison. The precision (which depends on the x-ray counts in the peaks of interest) and the accuracy (which depends on a reference, i.e., a standard material of known composition to compare to the unknown), were not investigated. The silicon wafer used for the device fabrication is also the micro cooler heat sink. To provide electrical insulation for the device, a 850 nm silicon dioxide layer is grown on the Si wafer. PR is spun cast defining a lift-off pattern for the hot (bottom) connectors and electrical connectors (pads). These connectors are Cr/Au/Ti/Pt layers grown by E-Beam evaporation. The Au and Pt layers are 200 nm and 20 nm thick, respectively. The Cr and Ti are 20 nm thick seed layers. The Pt, which has an electrical resistivity about 5 times larger and a thermal conductivity about 5 times smaller than Au, is used for its good adhesion to the columns, while preventing the diffusion of Au. Each column of the thermoelectric element is patterned consecutively before evaporation using an AZ9245 PR mold, which is where the n-type (or p-type) thermoelectric element will be formed.

Figure 5. X-ray diffraction pattern of co-evaporated (a) Sb2Te3 and (b) Bi2Te3 films. The measured peaks agree with the Powder Diffraction File

The Sb2Te3 and Bi2Te3 thermoelectric elements deposited on the hot connector pattern are shown in annexure-9. Micro thermoelectric coolers with up to 300 pairs of columns with cross-sectional areas equal to or larger than 7 μm x 7 μm are being fabricated. Current yield limitations are due to the deformation of the PR patterns (which define the thermoelectric elements) during the long exposure time of the PR to temperatures ranging from 70°C to 106°C. In some cases, mainly in devices with large column cross-sectional area (e.g., 30μm x 30 μm), a shifted column can reach the bottom connector next to it, or even the other column of the pair, leading to the device failure. Also, over hard baked PR is left at the borders of the columns, affecting the subsequent PR patterning. The use of a high temperature PR and an alternative method for patterning the columns (such as shadow mask) are being explored.
III. THE BACKGROUND OF THE HVAC SYSTEMS MODELING

The commercial and residential buildings are facing a new era of a growing demand for intelligent buildings world-wide. Intelligent buildings are referred to as energy and water saving, and they provide healthy environments. The first intelligent building was introduced in the late 1970s when buildings were equipped with IT equipment. The developments of the improved building and AHU models are essential to meet the requirements of an intelligent building. The HVAC system modeling evolution of research has been reflected on the representation of the indoor thermal behavior by development and enhancement of identification of buildings and AHU equipment. In general, research on indoor thermal comfort can be divided into two main categories: design-oriented research and research-oriented design as explained by Fallman. This study followed the second category where it depends on the previous research outcomes to develop a design that enhances the indoor thermal comfort.

IV. THE EVOLUTION OF THE HVAC SYSTEM MODELING

Building and AHU modeling has been used for decades to help the HVAC system scientists design, construct, and operate the HVAC systems. The pioneering development in the building and the HVAC system equipment industry is the heat conduction equation model by Joseph Fourier published in 1822, which is the most cited model. The earlier simulation work in building structure by Stephenson and Mitalas on the response factor method significantly improved the modeling of transient heat transfer through the slabs, the opaque fabric, and the heat transfer between internal surfaces and the room air. The heat balance approaches were introduced in the 1970s to enable a more rigorous treatment of building loads. Rather than utilizing weighting factors to characterize the thermal response of the room air due to solar incident, internal gains, and heat transfer through the fabric, instead, the heat balance methodology solves heat balances for the room air and at the surfaces of fabric components. Since its first prototype was developed over two decades ago, the building model simulation system has been in a constant state of evolution and renewal. Numerical discretization and simultaneous solution techniques were developed as a higher-resolution alternative to the response-factor methods. Essentially, this approach extends the concept of the heat balance methodology to all relevant building and plant components. More complex and rigorous methods for modeling of the HVAC systems were introduced in the 1980s. Transient thermal capacity of the wall and the indoor air is lumped and considered that the time series of disturbances (such as weather and internal loads) and occupational programs are known because they used model predictive control (MPC) which proposed an unconstrained optimal control algorithm to solve the load estimation problem. They obviously have imposed many assumptions to facilitate the calculations of heating load, which leads to lack of accuracy in the results. In addition, they used a single-input single-output (SISO) type model that does not consider the moisture transmission, an important element in deciding thermal comfort. For the air-handling unit (AHU) mathematical model, Wang et al. built models of heat exchanger for air-handling unit based on the conservation of energy and applied thermal balance equation on control volume for heat exchanger. This model is characterized as a SISO model since it does not take into account the effect of the mixing air chamber and assumed that the temperature of air supplied to the conditioned space is equal to the surface temperature of heat exchanger. Furthermore, they neglected the humidity of the moisture air supplied to the conditioned space because they do not want to include the effectiveness of humidity variation on thermal comfort. Therefore, they supposed that the type of cooling coil is of a dry type and that there is no indoor latent load.

V. FABRICATION OF DEMO MODEL OF HVAC USING TEC

We are replacing the whole existing HVAC system (Compressor, Electromagnetic clutch, Condenser, Receiver/drier, Metering devices, Evaporator, Refrigerants, Hoses and blower) by the TEC System, two blowers and some electric equipment. The electric source provided to the TEC system by the battery as per the specification of TEC plate. The TEC system consists of a cooling coil surrounded by the TEC plates on four surfaces of coil. The construction and working of cooling coil is just like an intercooler or radiator. The Four heat sinks are attached to the surface of TEC plate. A blower circulates the air from passenger compartment to the TEC and again the cool air is circulating from TEC system to passenger compartment. Another blower circulates the atmospheric air from all heat sinks and controls the temperature of heat sink.

8.1. Parts
Thermoelectric plate- 1plate Specification-
Part no. - ISA-T1-D-18-L
Length-40mm
Width-40mm
Voltage (Vmax) - 15.4 v

8.2. Equipment
- Blower (12V, 3A)
- Transformer (12V, 3A)
- Aluminum heat sink
- Temperature difference (∆T) = 68o
- Transformer (12V, 3A)
- Blower (12V) - 2 pieces

Figure 6. Demo model of HVAC using TEC.
Advantages of Thermoelectric Cooler

Ability to Cool below Ambient: Unlike a conventional heat sink whose temperature necessarily must rise above ambient, a TE cooler attached to that same heat sink has the ability to reduce the temperature below the ambient value.

Ability to Heat and Cool with the same module: Thermoelectric coolers will either heat or cool depending upon the polarity of the applied DC power. This feature eliminates the necessity of providing separate heating and cooling functions within a given system.

Precise Temperature Control: With an appropriate closed-loop temperature control circuit, TE coolers can control temperatures to better than ±0.1°C.

High Reliability: Thermoelectric modules exhibit very high reliability due to their solid state construction. Although reliability is somewhat application dependent, the life of typical TE coolers is greater than 200,000 hours.

Electrically "Quiet" Operation: Unlike a mechanical refrigeration system, TE modules generate virtually no electrical noise and can be used in conjunction with sensitive electronic sensors. They are also acoustically silent.

Operation in any Orientation: TEs can be used in any orientation and in zero gravity environments. Thus they are popular in many aerospace applications.

Convenient Power Supply: TE modules operate directly from a DC power source. Modules having a wide range of input voltages and currents are available. Pulse Width Modulation (PWM) may be used in many applications.

Spot Cooling: With a TE cooler it is possible to cool one specific component or area only, thereby often making it unnecessary to cool an entire package or enclosure.

Ability to Generate Electrical Power: When used "in reverse" by applying a temperature differential across the faces of a TE cooler, it is possible to generate a small amount of DC power.

Environmentally Friendly: Conventional refrigeration systems cannot be fabricated without using chlorofluorocarbons or other chemicals that may be harmful to the environment. Thermoelectric devices do not use or generate gases of any kind.

IV. CONCLUSION

Bi2Te3 and Sb2Te3 films have been deposited by co-evaporation of the elements, and the Seebeck coefficient and electrical resistivity were measured. The thermoelectric films with the highest electrical power factor, αS 2/ρe, have αS and ρe equal to -84 μV/K and 2.4x10^5 Ω-m (n-type film deposited with a maximum substrate temperature of 94 oC), and 120 μV/K and 1.9x10-5 Ω-m (p-type film deposited with a maximum substrate temperature of 90 oC). By using this plate we fabricated the demo model of HVAC (Heat Ventilation and Air Conditioning System) Using TEC (Thermoelectric Couple). Although the energy savings vary depending upon assumptions, it is clear that our experimental control system significantly reduced chilled air usage, and we estimate an energy savings of up to 24% over the standard HVAC control system that was running previously. It accomplished this by only cooling areas as much as required to maintain occupant comfort, and not cooling areas where occupants were not present. It also worked to maintain room temperatures at an equitable level for all involved. It was able to do all of this as a result of an ultra-low-power, wrist worn sensor node, which made the building aware of its occupants’ state via sensor data, and simple ‘hot’ and ‘cold’ button presses. These energy savings were the direct result of improving user comfort. In a well-functioning building, it is not the case that the temperature is either too hot or too cold, but rather that it is too hot or too cold for particular individuals: the air is not being distributed effectively. A number of personal cooling systems are commercially available, but these are expensive, and in some cases impossible to install (e.g. under floor systems). Our system overcomes these limitations by using wireless sensors and actuators, enabling the retrofit of older and less efficient buildings. Indeed, it exceeded the 80% comfort goal, which all commercial buildings aspire to, but very few meet. Our future work will explore longer studies involving more people and an entire building that we can control year-round without extensive retrofitting (as it is already equipped with a modern HVAC system). We will also explore variations on the wearable sensor, perhaps wearing it elsewhere on the body or integrating it into a watch, which would be more comfortable for our users. We will explore ways of bet-ter accommodating transients (when users transition between thermal environments), and mining all sensor data (including integrated activity level) for inferring comfort. We are also integrating our system with mobile phone applications and a pervasive display network installed throughout our building to explore aspects of persuasive computing - showing users how the system is working to keep them comfortable while reducing energy consumption and encouraging them to accept a wider range of comfort in exchange for energy impact.

V. REFERENCES


