Eighth International IBPSA Conference
Eindhoven, Netherlands
August 11-14, 2003

ESTIMATING PERFORMANCE OF THERMAL DISPLACEMENT HVAC SYSTEMS USING HEAT BALANCE-BASED SIMULATION PROGRAMS

Thomas A. Lunneberg, P.E.
CTG Energetics, Inc.
Irvine, California 92618
United States of America

ABSTRACT

This paper will address the shortcomings of typical heat balance-based HVAC design and analysis software when applied to thermal displacement ventilation (TDV) system design. The performance characteristics of thermal displacement systems that lead to inaccurate calculations from heat balance-based programs are discussed. Finally, the paper presents an approach for estimating the performance of TDV systems using existing heat-based calculation tools that responds to most of the significant differences between overhead mixing systems and thermal displacement systems.

INTRODUCTION

Thermal displacement ventilation (TDV) systems – essentially, HVAC air distribution systems that supply conditioned air at or near the floor and extract it near the ceiling - have been used in commercial buildings in some parts of the world (Europe, notably) for many years. This is not surprising when one considers that the buoyancy of rising air as it is warmed by people, lights, and equipment can carry heat and indoor pollutants (Figure 1) up and out of an air conditioned space, leading to enhanced indoor air quality, improved thermal comfort, and increased energy efficiency.

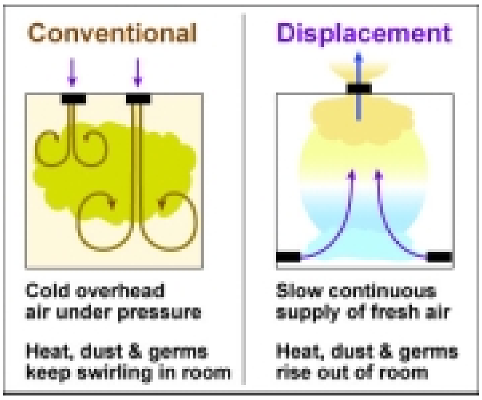

Figure 1: Comparison of Conventional Overhead Air Delivery with Displacement Delivery.

The use of thermal displacement systems in the United States, however, is still in its infancy. Driven in large part by increasing emphasis on sustainable design practices and an impetus to provide healthier indoor environments, many owners and developers are asking their engineers to design TDV systems for their new buildings. Unfortunately, many U.S. engineers and architects have little experience with the design and analysis of thermal displacement systems. As a result, many approach this task from an incorrect perspective – namely, that the thermal behavior of a displacement system is similar to that of a traditional overhead "mixing" system. The result is that poorly designed systems are being introduced into the marketplace. Such systems tend to deliver too much supply air, do not adequately address dehumidification needs, and frequently have overly complex control systems. Improperly designed systems such as these do not properly represent the benefits of thermal displacement. Unfortunately, stories about such problems lead many to the conclusion that the technology is ineffective.

Particular interest has been expressed towards applying TDV to classroom applications in the U.S. because of the potential for energy efficiency, initial cost savings, and better air quality for students. Because a TDV system can effectively remove heat from such spaces, it can improve comfort in schools where no means of mechanical cooling is to be provided. Also, because of the high minimum ventilation requirements for densely occupied classrooms, a TDV system employing 100 percent outside air (e.g. no air is recirculated) can provide an extra measure of indoor air quality because germs and other airborne pollutants are drawn up and out of the occupied space instead of mixed and recirculated.

Until reliable simulation tools are available to the consulting engineering profession that can accurately calculate the capacity requirements for TDV systems, some means for estimating performance of such systems is necessary. This paper presents several approaches that, while not a substitute for more rigorous analysis such as computational fluid dynamics (CFD), are sufficient for documenting the comparative benefits of TDV versus traditional overhead delivery.

SHORTCOMINGS OF CURRENT PRACTICE

When asked to design a displacement system, many HVAC engineers will attempt to employ the same load calculation methods that would be used for a conventional overhead system. The main problem with this approach is that heat balance-based methods assume complete mixing of the supply air with the room air, which neglects a key characteristic of the displacement approach – namely, that air will stratify according to differences in density if the air delivery pattern in the room does not disrupt the process.

The energy simulation program that is most commonly used in the United States for energy analysis and code compliance is called DOE-2. This program is quite capable with respect to the range of energy efficiency measures that it is capable of evaluating. However, because it is based on a heat balance approach to load calculations, it cannot directly simulate the performance of a TDV system with acceptable accuracy.

A heat balance-based program assumes that complete mixing occurs between all air supplies associated with a particular space and that sources of heat gain within the space are homogenously distributed throughout the space. This approach works fine for overhead systems, where great care is taken in terms of diffuser selection and placement to encourage vigorous mixing of cold supply air with warmer room air (Figure 5).

For a TDV system, air mixing does not happen nearly as readily as with an overhead system. The heat generated by people, lights and equipment rises because of the buoyancy of warm air. Since there is no downward directed supply airflow from the ceiling, there is nothing to impede ascension of the warm air towards the ceiling. As a result, strata of defined temperature ranges (Figure 6) develop; the average temperature at the level of the room occupants is much lower than at the ceiling. Because complete air mixing does not occur – and because hot air can be drawn from the top of the space and exhausted from the building – the overall airflow and cooling requirements are lower for TDV than traditional overhead systems. As an example, only about 13 percent of the heat gain from the lighting system translates into cooling load (Table 1) in a standard classroom application with pendant-mounted lighting.

Thermal displacement ventilation was proposed for the classrooms of a new high school located in San Diego, California that is being designed in 2003. The original design was based upon a standard variable air volume cooling system capable of delivering 1600 CFM of supply air to each classroom. By employing a TDV system, the airflow requirement was reduced by more than 50 percent and the cooling load was reduced by 37 percent. Conveying the reasons that this was possible to both the school district officials as well as the project design team was a major undertaking, and underscores the point that TDV systems are not understood very well by many who could benefit from their use.

A comparison of the cooling load components for one of the 100 M^2 classrooms for overhead and displacement systems is presented below in Table 1:

Cooling Load Component	Overhead System	Displacement System
Lights	966 W	x 0.13 = 126 W
Occupants	1,464 W	x 0.30 = 439 W
Equipment	439 W	x 0.30 = 132 W
Building Envelope	878 W	x 0.19 = 167 W
Total Space Load	3,748 W	864 W
Ventilation Load	4,100 W	4,100 W
Total Cooling Load	7,848 W	4,963 W

Table1: Cooling Load Components for Overhead and Displacement Ventilation Systems. The cooling loads indicated in the second column are calculated by multiplying the load in the first column by the factor shown in the second column. A TDV system would require 37 percent less cooling capacity than a traditional overhead system in this instance.

When engineers attempt to size DV systems using heat balance-based programs, the typical problems include:

- **Oversized airflow.** Because of the warmer supply air temperature used with DV systems (17°-19° C), most engineers assume that they will require about twice as much air delivery capability as a traditional (11°-13° C) system. They do not usually recognize that thermal stratification reduces the effective space volume that must be conditioned and removes a significant portion of the cooling load that must be handled with a mixing system.

- **Oversized cooling load.** Because heat balanced-based programs assume complete mixing between supply and room air, they are not capable of accounting for heat gain that is drawing up and out of the occupied zone of a room. Instead, these programs assume that all sources of heat gain in the space (except for some of the lighting heat gain in instances where return air is drawn directly through the light fixtures) must be neutralized with cold supply air.

The result of these problems are oversized systems that provide neither the comfort that the TDV concept promises nor the savings in initial and operating cost that are possible when the system is properly sized. Recommendation of such oversized systems has given some potential users the idea that TDV does not deliver the benefits that are frequently touted.

ALTERNATIVE METHODS FOR ESTIMATING TDV PERFORMANCE

Recognizing that a heat balance-based approach will overestimate cooling and airflow requirements, the author has experimented with several approaches for estimating TDV performance with such programs. These methods, though not exact, can be applied individually or together in order to provide a reasonable estimate of performance and energy use that will be sufficient to determine feasibility during initial project stages. To achieve the best performance, we recommend that more rigorous analysis methods, such as computational fluid dynamics, be used during the detailed design phases.

It must be stressed that those who are unfamiliar with the thermal behavior of TDV systems should be careful when employing these methods. In addition, a solid familiarity with the capabilities and syntax of the simulation program being used is essential. Finally, because much of the validity of these methods is tied to quality of the CFD modeling and its similarity to the space being simulated, it is helpful to have experience with (or at least access to somebody with experience with) the CFD results that are being referenced.

Method #1: Redistribute Internal Heat Gain Sources. One method that has been used with success to estimate TDV performance is to relocate some portion of heat gain sources from the conditioned space into the return air plenum. For example, using the DOE-2 program it is possible to specify the percentage of lighting heat gain that is introduced to the space and how much is passed directly to the return air plenum. CFD analysis by the author's firm has predicted that only about 13 percent of heat gain from lights enters the space in TDV applications for high school classrooms. Correspondingly, 87 percent of the heat is passed directly to the plenum where is can either be exhausted from the building or recirculated. Based on the CFD results, we consider it reasonable to apply these percentages in a heat balanced-based energy simulation. The method is reasonable, but only to the extent that the space that is being modeled closely resembles the space that was evaluated with CFD.

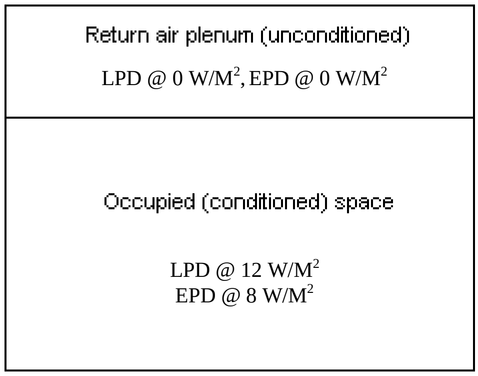

Figure 2: Cross-section view of typical room showing conditioned and unconditioned spaces, with typical lighting power density (LPD) and equipment power density (EPD). The total internal heat gain from these sources totals 20 W/M^2.

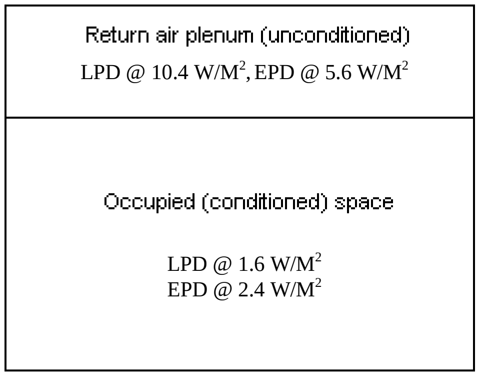

Figure 3: To simulate the reduced heat gain from lighting and receptacle loads, much of the load is reassigned to the unconditioned return air plenum. The effect is that cooling loads in the conditioned space are reduced while the return air temperature is increased. The total gain from lights and plugs is unchanged, however, it has been apportioned differently between conditioned and unconditioned space.

This method can also be applied to other heat gain sources, such as those of computers, copiers and other equipment that gets plugged into the wall socket. The problem that is encountered with most simulation software that we are familiar with is that there is no way to directly apportion plug loads between the conditioned space and the associated return plenum. One way to work around this typical limitation is to add the equipment heat gain to the lighting power density (because this input can usually be apportioned) and decrease the equipment power density accordingly. The overall accounting of heat gains will be correct but the individual values will be intentionally changed.

Another approach is to override the typical internal heat gain assumptions for the return air plenum (e.g. there is neither lighting nor equipment located in the plenum) and actually specify sources of heat gain in the plenum (Figures 2 and 3). The heat gain in the conditioned space should be reduced by a corresponding amount such that the overall heat gain remains unchanged. The change is limited to the location of the heat gain between conditioned and unconditioned space.

The primary advantage of this method is that it will estimate the reduced heat gain in the conditioned space, and therefore the program will calculate lower airflow and cooling rates. In addition, because heat gain is transferred to the return air stream via the plenum space (either via direct air return through the plenum or via return air ducts located in the plenum) the average temperature of the return air will increase, as would be expected with a displacement ventilation approach. The implication is that energy conserving building system components that are affected by return air temperature (for example, differential air-side economizer controls) will be simulated more accurately using this method than other approaches where the return air temperature is not affected.

The main disadvantage of this approach is that it leads to confusing program outputs. On a recent municipal project in Santa Monica, California, the local electric utility planned to pay a financial incentive to defray the cost of installing an underfloor air distribution system. The author's firm employed the strategy described above to account for thermal stratification, but the seemingly unexplainable changes in lighting and equipment use in the program output files led the utility representatives to request that a simpler method be employed. Even though they accepted the conceptual argument for redistributing the internal heat gains, they were fearful that the unusual appearance of the results would catch the eye of the Public Utilities Commission.

Method #2: Redistribute Building Envelope Heat Gain. Just as the heat from internal sources such as people, lights and equipment rises within the conditioned space, so does heat gain from the building envelope. Air that is warmed by solar gain through the glass and conduction through glass and wall assemblies rises up the exterior wall and directly towards the exhaust collection point. CFD analysis shows that only about 19 percent of the heat gain through the vertical surfaces translates into cooling load for a TDV system. To simulate this effect, a larger amount of wall and glass area can be associated with the return air plenum (typically, an unconditioned space that is 1 to 1.5 meters tall, located above the conditioned space on each floor of a building). The result is that more heat gain is routed to the return air system, and less to the conditioned space. At a qualitative level, this mimics what happens in real TDV systems: The result of stratification and overall lower airflow and exhaust rates is that return air temperatures are quite a bit higher than in a traditional overhead system.

A potential downside to this approach is that it will underestimate the amount of daylight that enters the space, which would make any daylighting control system calculations (systems that dim the lights automatically in response to ambient daylight levels) inaccurate. Accordingly, this method would only be appropriate for use in applications where the daylighting control is not being considered.

Another potentially significant disadvantage to this approach is how the reconfigured glazing will impact heat loss and heat gain in the conditioned space during unoccupied periods. For example, the advantages offered by TDV are not evident during overnight and weekend periods when the HVAC system is in a setback mode and the fans are turned off. During these times, heat loss and gain through the glazing should be transferred to the conditioned space. As a result, this method would underestimate the heating and cooling requirements when the HVAC system is initially energized to overcome the accumulated heating or cooling load after periods of unoccupancy.

Method #3: Reduce Volume of the Conditioned Space. Because the HVAC system is intended in most cases to provide comfortable temperatures at the level of the occupants (from zero to two meters above the finished floor), some simulation experts have proposed that intentionally decreasing the volume of the conditioned space, in combination with the other methods previously described, would be a reasonable way to account for thermal stratification. For example, if the floor to ceiling height of a classroom is three meters and the floor area is 100 M^2, the total volume is 300 M^3. If one were to assume that, because of stratification, comfortable temperatures only need to be provided up to a height of two meters above the finished floor then the volume of air that must be cooled to the preferred temperature would be reduced by one-third.

Method #4: Establish Vertical Thermal Zones
In an effort to simulate thermal stratification, it has been proposed that establishing a series of vertical thermal zones, each with a different space cooling temperature setpoint, would be an effective way to account for stratification (Figure 4). For example, if the three distinct temperature bands shown in Figure

6 were each designated as a thermal zone with a thermostatic setpoint equal to its average temperature, a heat balance-based program would calculate reduced airflow and cooling loads for the warm spaces closer to the ceiling. Some discretion would have to be applied with respect to how much of the each source of heat gain would be apportioned to each vertical zone.

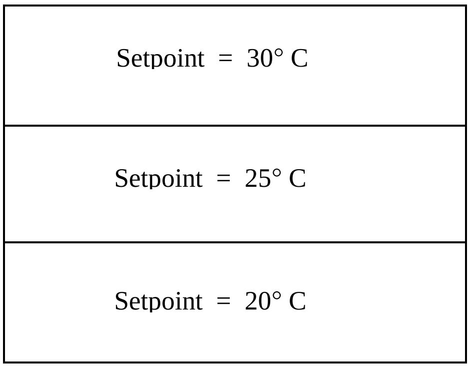

Figure 4: The impact of thermal displacement on cooling and airflow requirements can be estimated by dividing a room into distinct vertical zones, each with its own design cooling temperature.

CONCLUSIONS

While none of these methods are rigorous from a theoretical standpoint, they are intended to provide better results than would be achieved without applying any corrective measures to heat balance-based simulations of TDV systems. In California, where the State approves which software will be used to document compliance with the State Energy Code (known as Title 24), software developers, legislators, plan checking departments and design professionals are seeking a standardized, reasonable approach to simulating these increasingly popular air distribution systems. Until the time comes when the State approves programs that can model airflow, in addition to all of the required capabilities for other aspects of building design, it is inevitable that some amount of estimation will have to be applied.

In 2003, the author's firm will be preparing a handbook that provides more detailed information on methods to simulate TDV systems using heat balance-based programs. It is our intention to develop several CFD models for different building types, and then compare the results achieved with our estimation methods versus what is calculated with the more capable CFD program.

ACKNOWLEDGEMENTS

The author would like to thank Steven Long and Marc Cohen of CTG Energetics, Inc. for their efforts on the CFD analyses presented in this paper.

In addition, the efforts of the Collaborative for High Performance Schools (www.CHPS.org) to promote thermal displacement ventilation in school environments are greatly appreciated. Figure 1 is taken from the CHPS HVAC training materials.

Finally, the author was inspired by discussions with Clark Bisel of Flakt+Kurtz in 1996 about this topic during meetings in Santa Monica, and discussions with Martyn Dodd of Energysoft LLC in 2001.

REFERENCES

Yuan, Xiaoxiong. *Performance Evaluation and Design Guidelines for Displacement Ventilation*. ASHRAE Transactions. 1999. V. 105. Pt. 1. www.ashrae.org.

Best Practices Manual, published by the Collaborative for High Performance Schools (www. CHPS.org)

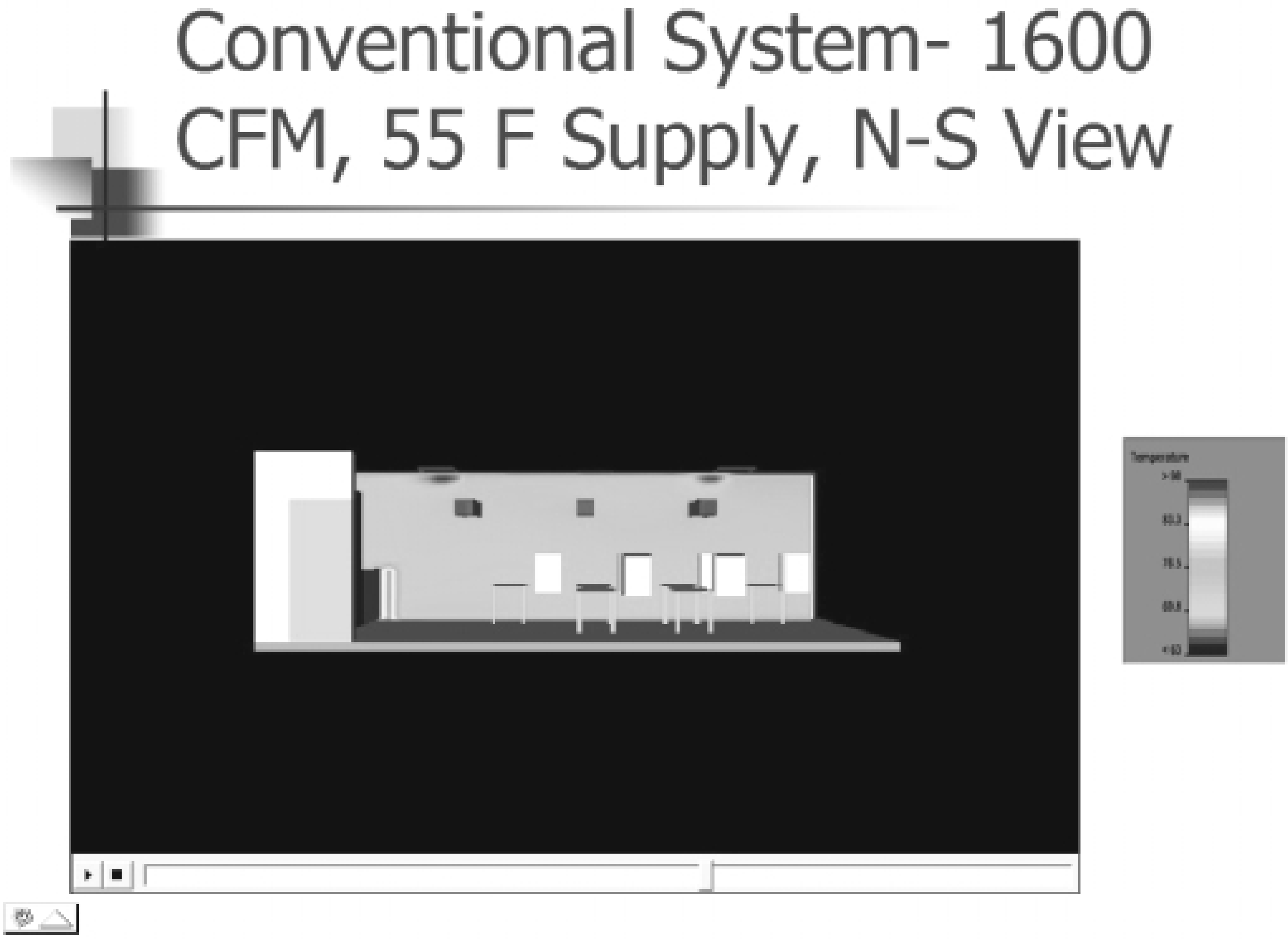

Figure 5: Conventional Overhead Air Distribution System. This cross section of a 100 M^2 classroom CFD model of air temperature distribution predicts uniform space temperatures from floor to ceiling. The coolest temperatures are located at the supply air diffusers. The entire volume of the classroom is cooled to a comfortable temperature even though occupants only experience the thermal environment from floor level up to about 2 meters above the floor.

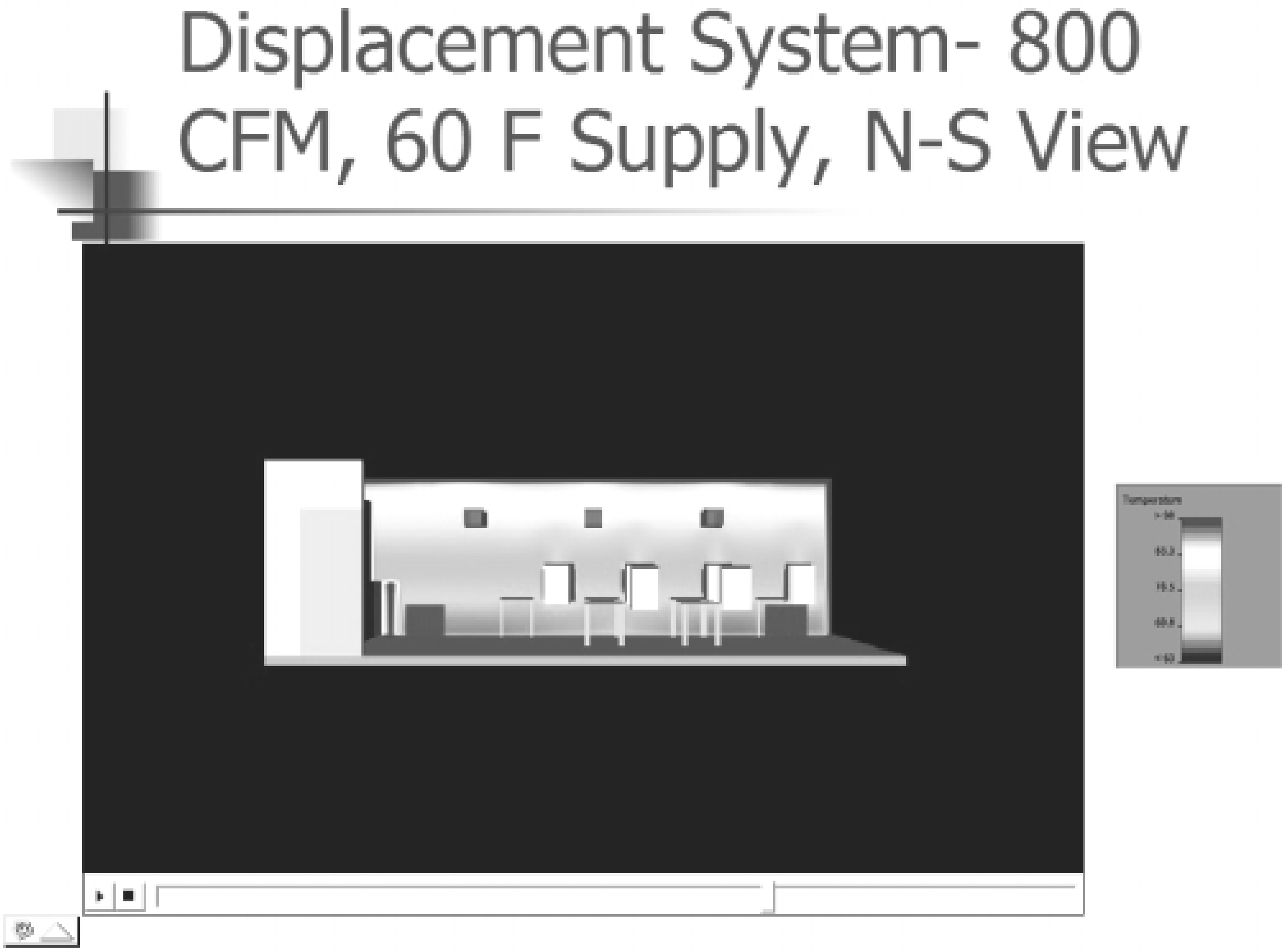

Figure 6: Thermal Displacement Ventilation System. This cross section of a 100 M^2 classroom CFD model of air temperature distribution predicts that stratification occurs when air is supplied at floor level at a low velocity. Acceptable temperatures are found at the level of building occupants, whereas there is a layer of very warm are located just below the ceiling.