Thermal Comfort Analysis of Personal / Task Cooling Approaches Driven by Radiant and Conductive Strategies using CFD

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ABSTRACT: It might be worthwhile to explore the possibility of developing personal / task cooling strategies that use radiant and conductive means of heat transfer; assisted by appropriate ventilation strategies as part of Task / Ambient Conditioning (TAC) approaches, as against cooling an entire volume of air in a space. Apart from energy savings, these strategies could potentially lend themselves to an adaptive model of thermal comfort, with greater occupant control over their thermal environment, which would further lead to enhanced occupant satisfaction and improved productivity. This paper explores the application of radiant and conductive strategies to TAC with an experimental simulation setup for analysis of the same; presents the methodology used in the analysis of such hybrid / composite systems and concludes with a comparative analysis of TAC (using radiation and conduction) with conventional air-conditioning; in terms of comfort – in the specific context of an office setting, for space cooling. The tool used for this research is the commercial Computational Fluid Dynamics (CFD) software developed by Flomerics Inc.; Flovent™ Version 4.1. The analysis of flow and heat transfer in buildings and an ability to predict thermal comfort are the principal applications for which this software was developed.

Conference Topic: 2 Design strategies and tools
Keywords: personal / task cooling, simulation, computational fluid dynamics, thermal comfort

INTRODUCTION

TAC as an alternative to conventional Heating, Ventilation & Air-Conditioning (HVAC), has been an ongoing subject of research for some time now (Bauman & Arens, 1996). Most of these approaches employ convection-driven Desk Displacement Ventilation (DDV) strategies.

There are a range of conduction-driven personal cooling solutions that are being tested and developed today as well as some that are commercially available (Bryan & Deshmukh, 2003) - these include cooled vests, cooled mats and cooled seats. One such cooled seat, for application in outdoor urban spaces has been developed and tested for surface temperatures (Bryan & Deshmukh, 2003). There is also a lot of interest in the field of cooled and heated seats in the automobile industry; primarily to do with reducing vehicular auxiliary loads and therefore, fuel consumption (Farrington, Brodt, Burch, & Keyser, 1998). Cooled and heated seats are also available as optional accessories in the high-end luxury car segment ("Amerigon: Advanced thermal solutions", 2003).

There is also an increasing acceptance and application of radiant heating and cooling strategies in combination with appropriate ventilation strategies as an alternative to conventional air-conditioning (Watson & Chapman, 2002).

Many proprietary systems, of which two are – Johnson Controls' (USA) Personal Environment™ system (Lomonaco & Miller, 1997) and Mikroklimat's (Sweden) Climadesk™ - are available commercially; which promote the concept of personal controls over individual workspaces, to achieve enhanced employee productivity and savings.

A large portion of typical office occupants — about 40 out of every 100 — may be dissatisfied with their thermal work environment. Even a well-designed HVAC system leaves at least 10 out of every 100 occupants "too hot" or "too cold" (Hamilton, Roth, & Brodrick, 2003). TAC allows individuals to control the temperature in their personal space. This leads to greater satisfaction, and hence to productivity-related benefits.

Based on the literature reviewed so far, there seems to be very little application of radiant strategies and almost no application of conductive strategies to TAC approaches for space conditioning. Potentially, both conductive and radiant means of heat transfer could lend themselves very well to Personal / Task Cooling solutions for space conditioning. It seems plausible then to make the case for application of radiant and conductive strategies to TAC approaches, whereby the potential of personal control over thermal control and energy savings are combined.

There is then, a need to examine, with the use of suitable modeling techniques, the potential of these strategies in terms of providing comfort, and demonstrating the potential for energy savings and benefits in terms of productivity.

2. METHODOLOGY

2.1 Experimental Setup

The following passage describes the setup used for analysis:

1 Workspace = 9.29 sq.m. (3.04m X 3.04m) with a 1.52 m Passageway all around; Total Enclosure 37.17 sq.m. (6.09m X 6.09m)

Loads:

All internal and occupant loads have been taken from ASHRAE Handbook of Fundamentals 2001, Ch. 29.

Equipment Loads:

Computer: 65W; Monitor: 80 W; Printer: 25 W

Lighting Loads:

Task Lights: 9W CFL, 4 lamps; 13.42 W each

General Lights: T8, 4 luminaires, 2 lamps, 1200 mm, with Special Allowance Factor; each 56.4 W.

Occupant Loads:

One Person – Moderately active office work, adjusted M/F Value; 130W

External Loads:

External loads have not been considered - the enclosure is adiabatic, at the boundary of the solution domain - it is assumed that the said enclosure is within a conditioned space.

Space Conditioning:

Overhead Radiant Panels:

2 panels - 1.21m X 0.61m each, at 2.44m height. Initial temperature at 20°C.

Cooled Seat:

It is proposed that a cooled seat be used, similar to the ones used in the higher end of the automobile market. One particular prototype that uses a thermoelectric device as a heat pump, may be adapted for use in this setting, probably with batteries that may be charged at night. Seat and back surfaces are cooled, at 23°C; which has been chosen as it is the comfort temperature for the human body.

Ventilation:

A supply diffuser placed at the corner of the cubicle space, with two active jets, towards the cubicle, supplies air at a rate that is sufficient for ventilation purposes. The initial setting for this has been taken as 20°C supply air, at a rate of 9.44 L/s (per person).

On the return side, a return grille, exhausting air out of the conditioned space at a rate equivalent to the supply rate has been provided. This return has been provided within the cubicle space, diagonally across from the diffuser.

2.2 Simulation Setup

Office Equipment:

The office equipment (computer, large monitor and printer) have been modeled as cuboids with a fixed heat flow.

Lighting:

Task Lights: These have been modeled as solid sources, with a total heat source.

General Lights: These have been modeled as collapsed sources, with the direction of the heat flow towards the conditioned space; with a total heat source.

Thermal Mannequin:

The thermal mannequin has been modeled, with a total of 130W distributed proportionately over 21 body parts. Although this includes a sensible and latent component; for the purpose of this research, it has been modeled as a sensible source only.

Space Conditioning:

Radiant Panels:

The overhead radiant panels have been modeled as collapsed heat sources, with a constant temperature and the cold face directed towards the conditioned space. To begin with, these panels have been set at 20°C.

Cooled Seats:

The chair itself has been modeled as two cuboids for the seat and back, the cooling elements are provided with collapsed sources at the surface of the seat and back, at a constant temperature, and the cold face directed towards the body. To begin with, the cooled surfaces are taken to be 23°C.

Ventilation:

The supply diffuser has been modeled using a "square diffuser" element provided within the software. Optimization of this setting has been done with 2 negative and 1 positive steps of 2°C and 0.94 L/s, respectively. On the return side, a "fixed flow" unit has been provided. The flow rate for the parametric runs has been modeled so as to match the supply flow rate.

2.3 Optimization

Optimization of the TAC case has been carried out in two phases, Preliminary and Detailed, as outlined below.

Preliminary Optimization:

Preliminary optimization was carried out by comparing temperatures recorded at the monitor points and the distribution of temperatures and PMV indices across the room. This was carried out by first ascertaining the best combination of supply air temperature and flow rate and then by ascertaining the best combination of temperatures for the radiant panels and cooled seats.

Detailed Optimization:

Detailed optimization was carried out in the manner of trying to “engineer” comfort conditions by changing individual elements step by step. The temperatures recorded at the monitor points were only considered so as to ensure that these were not outside the acceptable boundaries of comfort and not for any quantitative comparison between scenarios, as in the Preliminary Optimization process. The focus here was more on achieving as even a distribution of temperatures and comfort indices across the space as possible.

2.4 Comparison

At both stages of optimization, the distribution of the relevant comfort indices across the space were compared with what would be achieved with conventional air-conditioning. For the preliminary case, supply air at 13°C (55°F) and a flow rate of 0.094 L/s (0.2 cfm) per sq. ft. was considered (as per ASHRAE 62-1999). For the detailed optimization case, supply air at 13°C (55°F) and a flow rate sized for thermal loads (treated as sensible only) was considered (as per ASHRAE Handbook 2001, Ch. 26).

The scenarios for both the optimization and comparison have been outlined in the following table:

Table I: Scenario Chart

	Supply Air		Panels		Seat
	Temp (°F)	Flow Rate (cfm)	Upper (°F)	Lower (°F)	(°F)
TAC Prelim. Optim.	68	20	68	68	73
	65	18	68	68	73
	65	18	65	65	72
HVAC Comp.	55	80	-	-	-
TAC Detailed Optim.	65	18	65	68	72
	65	18	65	70	72
	65	18	63	70	72
	65	18	60	70	72
	65	18	60	72	72
	65	18	60	73	72
	65	18	60	75	72
HVAC Detailed Comp.	55	82	-	-	-
	55	84	-	-	-
	55	86	-	-	-
	55	88	-	-	-

2.5 Comfort Metrics

In terms of comfort indices, it is accepted quite widely today, that air temperature by itself is not the best metric of comfort. Operative Temperature, which is a function of the air temperature and Mean Radiant Temperature (MRT), for the actual air velocity is a more widely accepted index. However, with regards to non-uniform, low-velocity systems, the Equivalent Homologous Temperature (EHT) or Equivalent Temperature (t_{eq}); which is a function of the Air Temperature and the MRT at a fixed low velocity has been more widely accepted, as a measure of non evaporative heat loss from the body (Nilsson, 2004). However, both the Operative Temperature and EHT are calculated for fixed air velocities.

Numerically, the Operative Temperature is the average of the MRT and the air temperature. In Flovent™, the Comfort Temperature is calculated as a function of the air temperature, the MRT as well as the air velocity in each cell, since, with an increase in air velocity, the air temperature has an increasing impact on the perceived temperature (Flomerics, 2003). In the sense that it is similar to the EHT index, it is a reasonable metric for the purpose of this study. The most widely accepted PMV-PPD indices too (Fanger, 1972), are calculated in Flovent™, as per the inputs required, for each air cell, based on the air temperature and MRT recorded for each cell (Flomerics, 2003). For the purpose of this study, the PMV index has been used to demonstrate the achievable thermal comfort along with the Flovent™ Comfort Temperature plots.

3. RESULTS ANALYSIS AND DISCUSSION

3.1 Preliminary Optimization

Based primarily on the temperatures recorded at the monitor points and the distribution of the comfort indices across the space, the best case supply air temperature and flow rate were chosen to be 18°C (65°F) and 8.5 L/s (18 cfm).

The surface temperatures for the radiant panels and the cooled seat were then optimized, the best case chosen being 18°C (65°F) for the panels and 22°C (72°F) for the seat. Tables II and III show the values recorded at the monitor points for the two-step process carried out. Figures 1 and 2 show the optimized case with distribution of the Comfort Temperatures and PMV across the space, for the best case achieved through this process.

3.2 Detailed Optimization.

The scenario chart in Table I, shows the process of optimization by changing individual parameters. At each of these steps, the distribution of the two comfort parameters / indices mentioned in 2.5 was examined and an appropriate parameter was then changed for the subsequent run. The best case for the detailed optimized case (for the PMV index) for TAC finally has supply air at 18°C (65°F) and 8.5 L/s (18 cfm); upper radiant panels at 16°C (60°F), lower panel at 24°C (75°F) and the cooled seat at 22°C (72°F). Figures 3 and 4 show the distribution of Comfort Temperatures and PMV across the space for the best case achieved through this process.

3.3 Comparison

Both the detailed and preliminary optimized TAC cases are compared qualitatively for the distribution of the comfort indices across the space. The preliminary optimization case is compared quantitatively as well, by examining the temperatures recorded at the monitor points.

Given that the PMV index is a function of the air temperature and the Mean Radiant Temperature (MRT) for the values of metabolic rate, external work, clothing level and insulation; whereas the Comfort Temperature index is a function of air temperature, MRT and air velocity for the loads described in the model, it is seen, understandably, that the distribution of these two indices across the space, are different.

The noteworthy aspect of the comparisons is that the TAC case offers a lot more flexibility and options as far as “engineering” preferred comfort conditions is concerned, and that too, at an individual level, with the supply air temperatures and flow rates constant. For the conventional HVAC case, this is pretty restricted as one can only adjust the flow rate of the supply air towards “engineering” the thermal environment and this too, will have to be done in a manner that will impact all occupants. The aspect of individual comparisons is seen to offer a great advantage in this regard.

Table IV shows the comparison of the monitor points’ temperature data for the TAC and the conventional HVAC. Figures 5 and 6 show the distribution of Comfort Temperatures and PMV for the best case chosen for conventional HVAC.

Table II: Optimization of Supply Air Parameters, Monitor Points' Data

Scenario	0	1	2	3
Square Diffuser : Square Diffuser Flow Rate (L/s)	9.44	8.50	7.55	10.38
20°C : Ambient Temperature (°C)	20	18	16	22
Head Front : Temperature (°C)	26.68	26.45	***26.19***	26.74
Chest : Temperature (°C)	24.98	24.85	***24.74***	24.98
Head Back : Temperature (°C)	20.00	20.00	20.00	20.00
Left Arm : Temperature (°C)	24.02	23.71	***23.50***	24.15
Right Arm : Temperature (°C)	20.00	20.00	20.00	20.00
Left Thigh : Temperature (°C)	23.64	23.53	***23.51***	23.74
Right Thigh : Temperature (°C)	20.00	20.00	20.00	20.00
Back : Temperature (°C)	23.00	23.00	23.00	23.00

Table III: Optimization of Radiant Panels and Cooled Seat, Monitor Points' Data

Scenario	0	1	2
Radiant Panels : Source	20°C	18°C	16°C
Cooled Seat : Source	23°C	22°C	21°C
Head Front : Temperature (°C)	26.40	24.99	***23.52***
Chest : Temperature (°C)	24.83	23.71	***21.89***
Head Back : Temperature (°C)	20.00	20.00	20.00
Left Arm : Temperature (°C)	23.74	22.11	***20.48***
Right Arm : Temperature (°C)	20.00	20.00	20.00
Left Thigh : Temperature (°C)	23.51	21.88	***20.25***
Right Thigh : Temperature (°C)	20.00	20.00	20.00
Back : Temperature (°C)	23.00	20.00	20.00

Table IV: Comparison of Task/Ambient Conditioning and Conventional HVAC, Monitor Points' Data

Scenario	0	1
Square Diffuser : Square Diffuser Flow Rate (L/s)	8.50	37.76
18°C : Ambient Temperature (°C)	18	13
Cooled Seat : Activated	Yes	No
Radiant Panels : Activated	Yes	No
Head Front : Temperature (°C)	24.87	22.84
Chest : Temperature (°C)	23.36	22.11
Head Back : Temperature (°C)	20.00	20.00
Left Arm : Temperature (°C)	22.23	20.30
Right Arm : Temperature (°C)	20.00	20.00
Left Thigh : Temperature (°C)	22.14	20.61
Right Thigh : Temperature (°C)	20.00	20.00
Back : Temperature (°C)	22.00	20.00

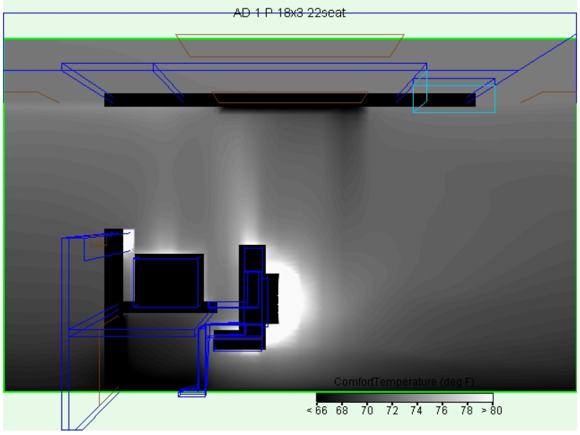

Figure 1: Comfort Temperatures, TAC, Preliminary

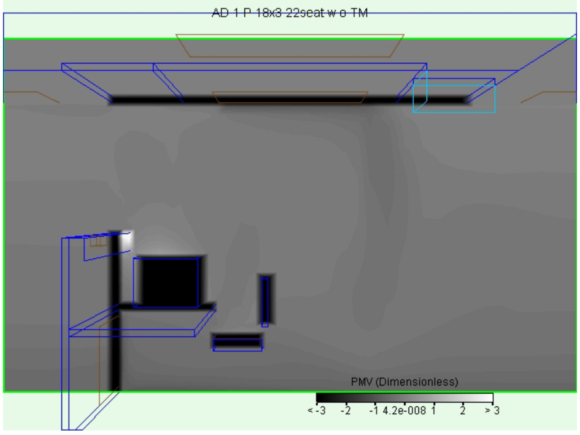

Figure 2: PMV, TAC, Preliminary

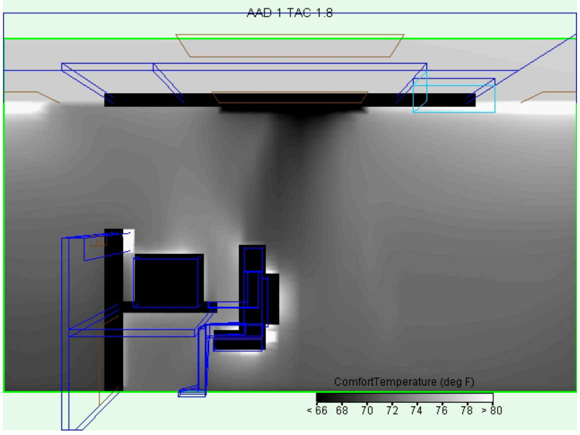

Figure 3: Comfort Temperatures, TAC, Final

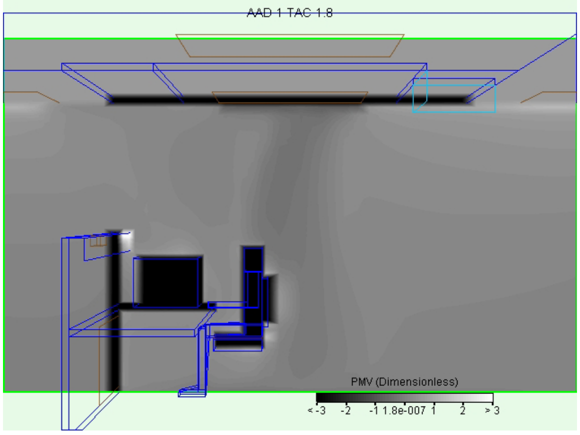

Figure 4: PMV, TAC, Final

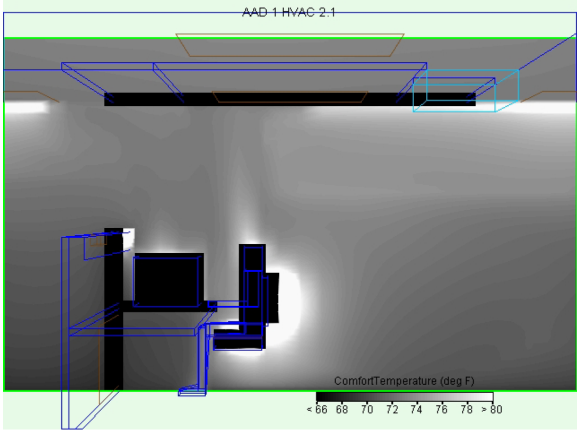

Figure 5: Comfort Temperatures, HVAC, Final

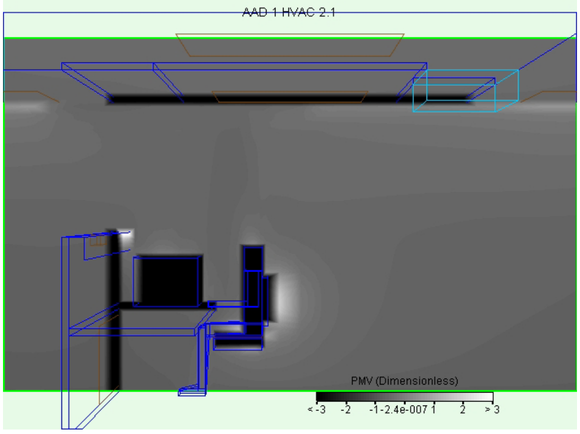

Figure 6: PMV, HVAC, Final

CONCLUSION

The cases discussed in the preceding text demonstrate the potential of TAC approaches using primarily radiant and conductive strategies.

It is seen that the distribution of Comfort Temperatures does not agree very well with the distribution of the PMV, especially for the TAC cases. This, as has been discussed earlier, is as one would expect – with the PMV-PPD indices being more suited to the conventional, “well-mixed” HVAC case.

Nonetheless, the ability to provide adequate comfort with TAC approaches using primarily radiant and conductive strategies, without changing the supply air temperatures and supply air flow rates once they have been optimized; has been adequately demonstrated for both indices considered in this study.

Furthermore, as demonstrated, radiant and conductive task cooling approaches also allow the potential of endless possibilities of occupant control over their thermal environments to the extent of separately controlling each individual cooling element so as to achieve the desired comfort conditions, without changing the general or ambient conditions. As such, these strategies would go a long way towards ensuring worker satisfaction and thus provide greater potential of benefits by way of increased productivity.

The potential with regards to energy savings, of radiant cooling over conventional HVAC has been demonstrated in the Literature Review. This study has demonstrated, to good effect, that with a task cooling approach that uses radiant cooling, these savings can be increased even more. Where most radiant cooling approaches would typically cover anywhere between 50%-70% of the overall ceiling area; in the cases demonstrated, even if one were to include the lower ceiling panels, the effective coverage in terms of overall ceiling area is just 6%. Hypothetically, if one were to consider even the seats to be cooled using a hydronic system, it goes up to only 8%.

The hypothesis stated at the beginning of the research, was that radiant and conductive TAC approaches had the potential to offer adequate comfort conditions and a potential for energy savings. It is seen from the results of the various cases that this hypothesis has stood true.

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