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Simulation of Displacement Ventilation and Radiative Cooling

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ABSTRACT

For thermal comfort and energy conservation reasons, displacement ventilation and radiative cooling systems are increasingly used. Simulation programs are general not able to correctly simulate such systems because of their one node approach for the air temperature. A procedure for creating DOE-2 inputs to simulate both system types each alone or in combination - without program code change - was developed, based on a more detailed new TRNSYS-Type, and validated against existing experimental data sets. The used approaches in DOE-2 are a two zone model for the displacement ventilation and a 'dummy' zone for the radiative cooling. A sufficiently good agreement shows that this is possible. The new TRNSYS-Type is a one zone model similar to the existing Type 19, but it simulates the temperature gradient in the room with 3 air nodes.

LIST OF SYMBOLS

T_{ac}	Air temperature in the centre of gain	[°C]
T_{ce}	Temperature of the ceiling	[°C]
T_e	Exhaust air temperature	[°C]
T_{af}	Air temperature near the floor	[°C]
T_s	Supply air temperature	[°C]
$\dot{q}_{lo}$	Heat power in the lower zone	[W/m2]
$\dot{q}_{up}$	Heat power in the upper zone	[W/m2]
$\dot{q}_h$	Heat source power	[W/m2]
$\dot{q}_{12}$	Heat flow from zone 1 to zone 2	[W/m2]
$\dot{q}_{21}$	Heat flow from zone 2 to zone 1	[W/m2]
Φ	Load split	[-]
ω_{ac}	Temperature efficiency in the centre of gain	[-]
ω_{af}	Temperature efficiency near the floor	[-]

INTRODUCTION

For reasons of thermal comfort, low-turbulence air supplies are becoming increasingly important. Because their capacity for heat removal is limited, the two tasks of cooling and air renewal must be split into two different systems. The cooling task is advantageously done by a radiant element, which also leads to an energy efficient solution due to low air transport energy. For air renewal, vertical directed ventilation (displacement ventilation) is adequate.

The simulation program DOE-2 [6] lacks both of these systems, which is one of the most frequently heard arguments against it. The goal was to find a way to create a practicable simulation model for radiant ceiling and displacement ventilation within this program, without changing the program code, by clever geometric input and, if necessary, by using the "functional input" feature of the program.

The parameters necessary for the DOE-2 model are calculated by a more detailed TRNSYS model [7]. This leads to the question why a more or less exact DOE-2 model is needed as the more detailed TRNSYS model is available. At first the concepts of the two programs are different. In DOE-2 the components and HVAC systems are predefined. By definition of parameters some components can be defined or suppressed. The TRNSYS components are defined by the user in FORTRAN routines and linked to each other by in- and outputs. But the so achieved individual applicability results in much more complex problems with the modelling. Numerical problems cannot be excluded. This requires exact knowledge of the user about the algorithms. DOE-2 on the other hand is a complete program which does not have instability problems. Input errors are documented by numerous and comprehensive error messages. Furthermore the computation times are much shorter with DOE-2 than with TRNSYS. Therefore the transfer of the parameters into a simplified model is sensible for some applications.

DISPLACEMENT VENTILATION

Most simulation programs are not able to simulate a temperature gradient over the room height because of there one node approach for the air temperature. For the simulation of a temperature gradient at least two air nodes are necessary.

The TRNSYS model room is a geometric one zone model with walls, windows and doors. It calculates the air temperature in three nodes and the temperatures of all surrounding surfaces. The heat transfer through the walls is calculated with the response factor technique. Taking into consideration the view factors of the different surface areas, of the heat source, and of the lighting system, the radiative balance is solved. At each surface and heat source, a convective heat transfer is applied. In every time step, the equation system is solved simultaneously.

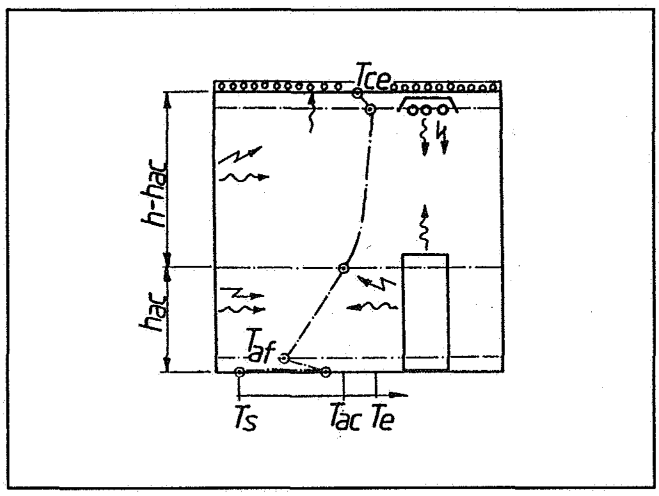


Figure 1: TRNSYS model room

Mathisen [2] shows in his measurements that the shape of the air temperature in a room varies with different loads. However, if one plots the air temperature as a dimensionless temperature difference in the centre of heat gains

$$\omega_{ac} = (T_{ac} - T_s) / (T_e - T_s) \qquad (1)$$

a dependency from the specific air flowrate can be shown. The same result was found by Mathisen in his study.

The temperature efficiency in the centre of heat gains for a typical room with various spec. heat gains in a stationary case is calculated with the model and shown in Figure 3.

In the same way it is possible to calculate the temperature efficiency near the floor (Figure 2).

$$\omega_{af} = (T_{af} - T_s) / (T_e - T_s) \qquad (2)$$

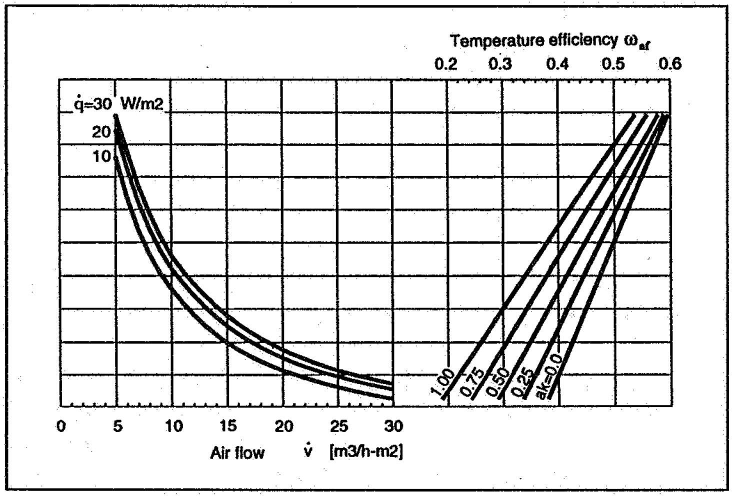


Figure 2: Temperature efficiency near the floor

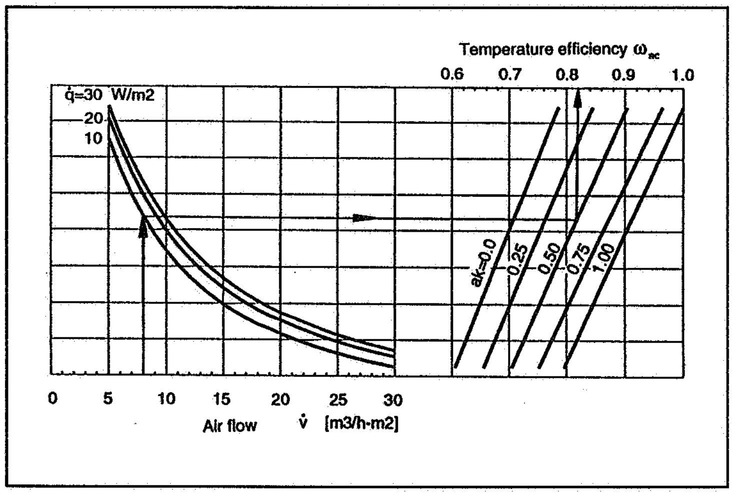


Figure 3: Temperature efficiency in the centre of gain

The validation of the dynamic behaviour of this model was done against measurements taken in a test cell.

Test room l, w, h		5.5, 4.4, 2.5	m
Airflow		5	m3/h-m2
Air supply temperature		20	°C
Centre of heat gain		1.1	m
Heat gain	Time 0-9 h	21	W/m2
	Time 9-24 h	0	W/m2
Lighting	Time 0-9 h	14	W/m2
	Time 9-24 h	0	W/m2

Table 1: Boundary conditions for the validation of the displacement ventilation model.

Figure 4 and 5 shows the good agreement of the TRNSYS simulation with these measurements.

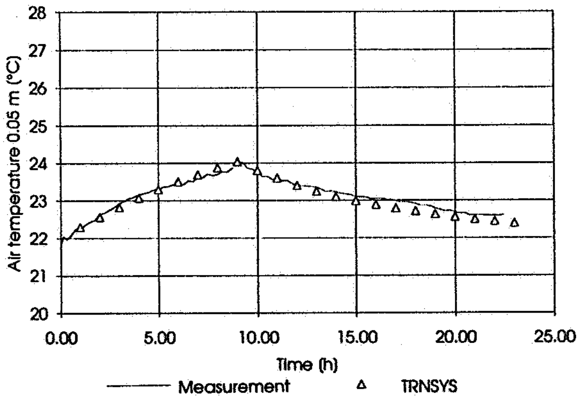


Figure 4: Air temperature near the floor.

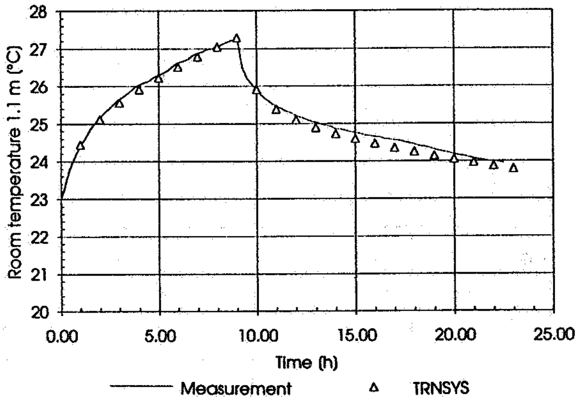


Figure 5: Room temperature 1.1 m above the floor.

The used DOE-2 approach is a two zone model. The room is separated into a lower zone with a height from the floor to the centre of heat gains and an upper zone covering the rest.

In general, a real heat source releases heat to the air by convection and to the surrounding surfaces by radiation. These surfaces exchange heat with each other by radiation again. This means that a heat flux also takes place between the two fictive zones. In DOE-2 this radiation heat exchange is not calculated. For this reason, the heat emission of the source is split into the two zones in such a way that the energy flows between them represent the real case.

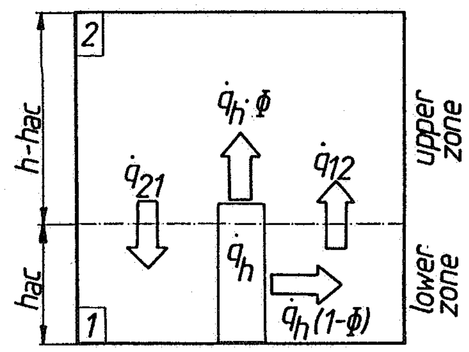


Figure 6: Real heat source and heat flows between the two zones.

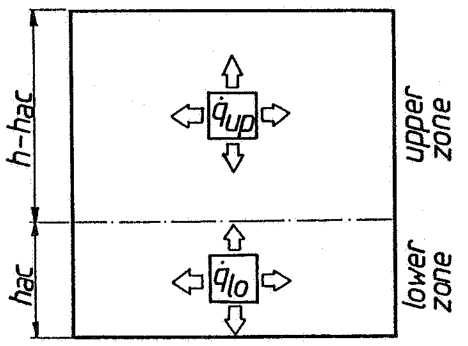


Figure 7: Modelled heat source distribution in the two zones.

$$\dot{q}_{lo} = \dot{q}_{21} + \dot{q}_h(1-\Phi) - \dot{q}_{12} \quad (3)$$

$$\dot{q}_{up} = \dot{q}_{12} + \dot{q}_h\Phi - \dot{q}_{21} \quad (4)$$

The heat gain split Φ in the steady state case is chosen in a way that - with a chosen air flowrate, a specific power of the heat gains and their convective portion - the temperature difference of the DOE-2 model corresponds to the data in figure 3 (TRNSYS simulation). With a constant load split Φ, the DOE-2 model also shows the dependence of the temperature difference on the specific air flowrate (Figure 8).

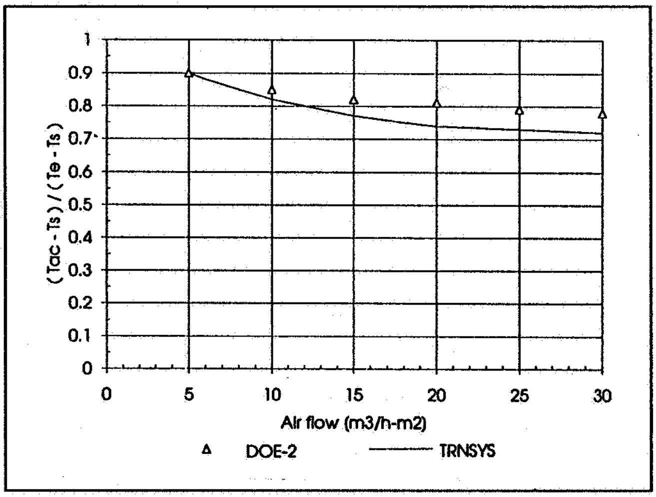


Figure 8: Temperature efficiency as a function of the airflow rate

For the evaluation of the DOE-2 approach in the dynamic case, also boundary conditions according to table 1 were used. The room temperatures on a height of 1.1 m obtained from the measurements cannot be compared directly with the DOE-2 data, because this program does not show the surface temperatures due to the weighting factor technique. For this reason the two models in DOE-2 and TRNSYS are compared.

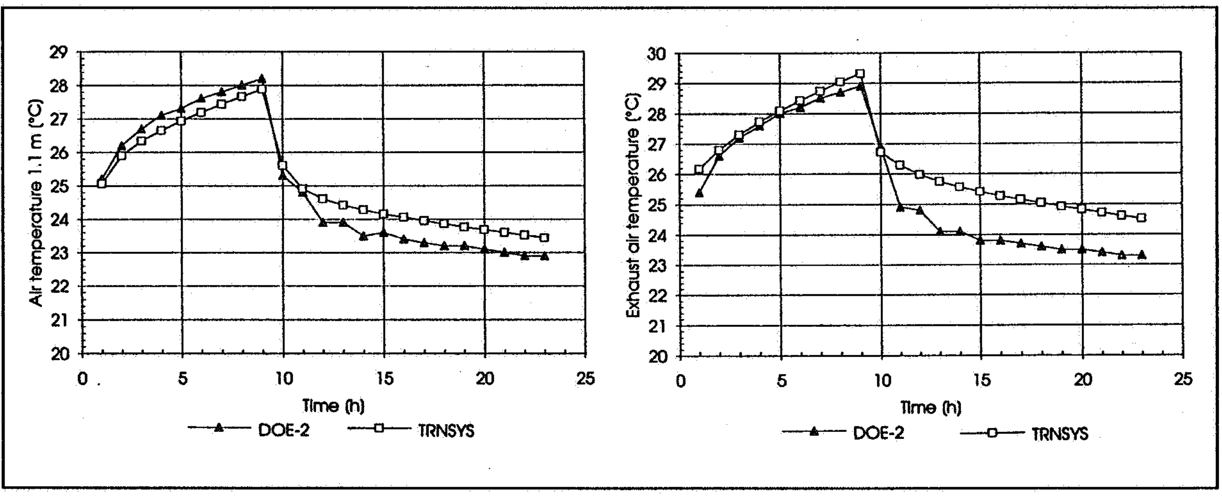


Figure 9: Comparison of DOE-2 and TRNSYS Air temperature 1.1 m above the floor

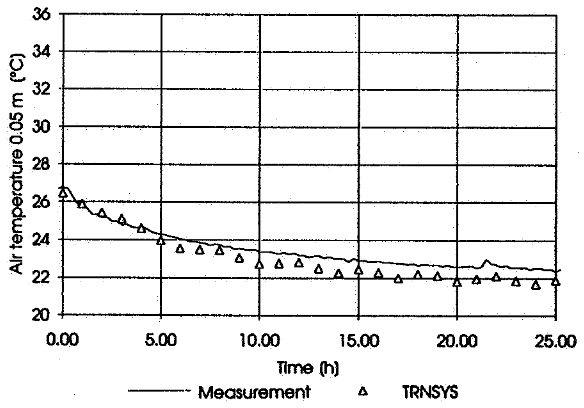
Figure 10: Exhaust air temperature

RADIANT CEILING

As shown in Figure 1, it is possible to have a radiant ceiling on the top of the TRNSYS room. The radiant ceiling can be either a quick metal or a concrete type. The validation was done against measurements in a test cell with a quick metal radiant ceiling. For the begin of the measurement the room was in steady state conditions at a temperature of 32 °C. The radiant ceiling was off and only the displacement ventilation system was on operation. At the begin of the measurements the operation of the radiant ceiling was also started.

Test room l, w, h	5.5, 4.4, 2.5	m
Airflow	6	m3/h-m2
Air supply temperature	20	°C
Water flow	730	kg/h
Water supply temperature	18	°C
Centre of heat gain	1.1	m
Heat gain always on	29	W/m2
Lighting always on	14	W/m2

Table 2: Boundary conditions for the validation of displacement ventilation and radiant cooling.



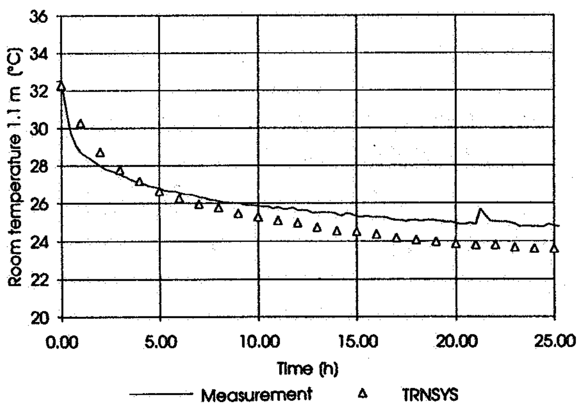


Figure 11: Air temperature near the floor.

Figure 12: Room temperature 1.1 m above the floor

In the DOE-2 model the radiant ceiling is modelled by a separate "dummy" zone on top of the room. The ceiling of the room is the radiant ceiling and through this surface the heat is transferred to the coolant. The dummy zone has supply and return temperatures that correspond to the supply and return of the coolant. In this way it is possible to connect this radiant ceiling to the necessary components, such pump, chiller, or cooling tower. Also, the control behaviour of the radiant ceiling can be examined. If the radiant ceiling is to be simulated in the two zone model (combined with displacement ventilation), its heat extraction power has to be split correctly to the upper and lower zone. As mentioned above, the DOE-2 program does not calculate the radiation heat fluxes across the two fictive zones. For this reason, for the calculation of the power distribution of the radiant ceiling, an external program was used (the new TRNSYS model was not available at that time). The result was then transferred to the simplified DOE-2 model. A fixed split of the areas of the ceiling to the zones is only possible if the portions of the heat transfer between the ceiling and the two zones are independent from the temperature difference between the air and the ceiling surface. This could be confirmed with the aid of the separate radiation model. The latter consists of the following parts:

- Radiant ceiling
- Exterior walls
- Windows
- Interior walls
- Floor
- Load plane for the simulation of the heat sources
- Lighting

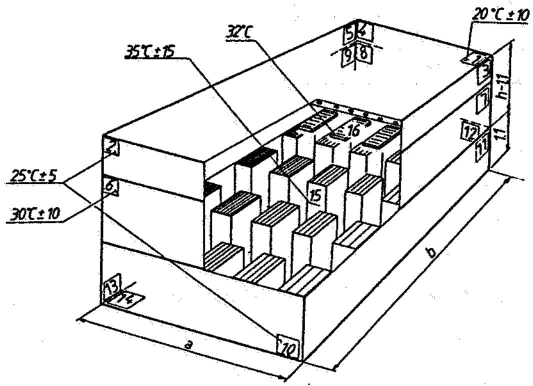
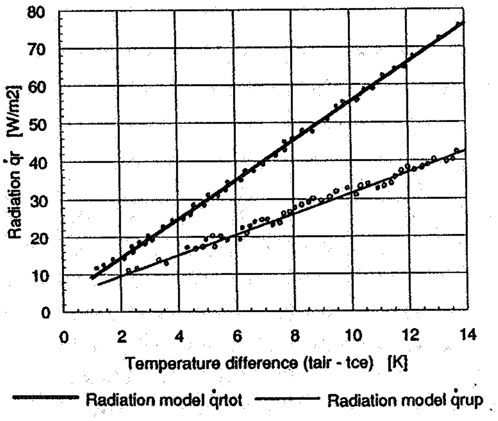


Figure 13: Geometry and temperatures of the radiation model

Based on the geometry, the program calculates the view factors between the radiation ceiling and the different surfaces. By choice of the temperature of the different surfaces, the radiative balance of the ceiling can be found. If the heat exchanges of all surfaces of the upper or lower zone are added up, the requested split of the radiative power is obtained. To make sure that a wide range of possible variations for the surface temperatures is considered with the simulation, these were varied by a random number generator within an admissible range according to the indications in Figure 13. 140 temperature variations were calculated for each parameter.



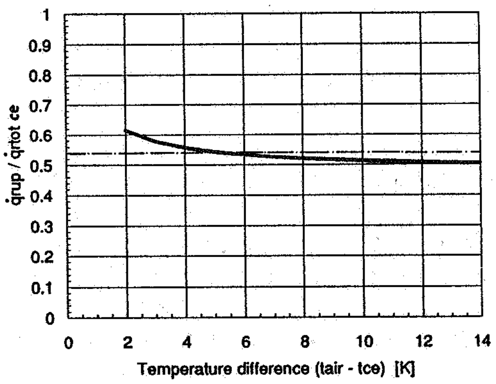


Figure 14: Total radiation power and portion in the upper zone.

Figure 15: Relation between the radiative power in the upper zone and the total radiative power.

From the large number of resulting points, the radiation of the ceiling is derived as a function of the difference between the air and the ceiling surface temperatures. If the relation between the radiation in the upper zone and the total radiation is plotted, it can be shown that this relation is nearly constant over a wide temperature range. The convective heat fluxes of the involved surfaces in the zones can be considered only roughly. The convectively generated airflow cannot be simulated sufficiently. Therefore, it is assumed in the DOE-2 model that the split of the convective heat flows to the two zones is equal to the radiative one.

For the validation the experiments No 12 and 15 in the thesis of Kuelpmann [1] were used. They have the following characteristic data:

Test room l, w, h	5, 4, 2.87	m	
	Test 12	**Test 15**	
Heat source	100.1	72.1	W/m2
Cooling power ceiling	85.1	63.0	W/m2
Air system cooling power	14.9	9.1	W/m2
Air flow rate	4.6	4.6	m3/h-m2

Table 3: Boundary conditions for the validation of the DOE-2 radiation model

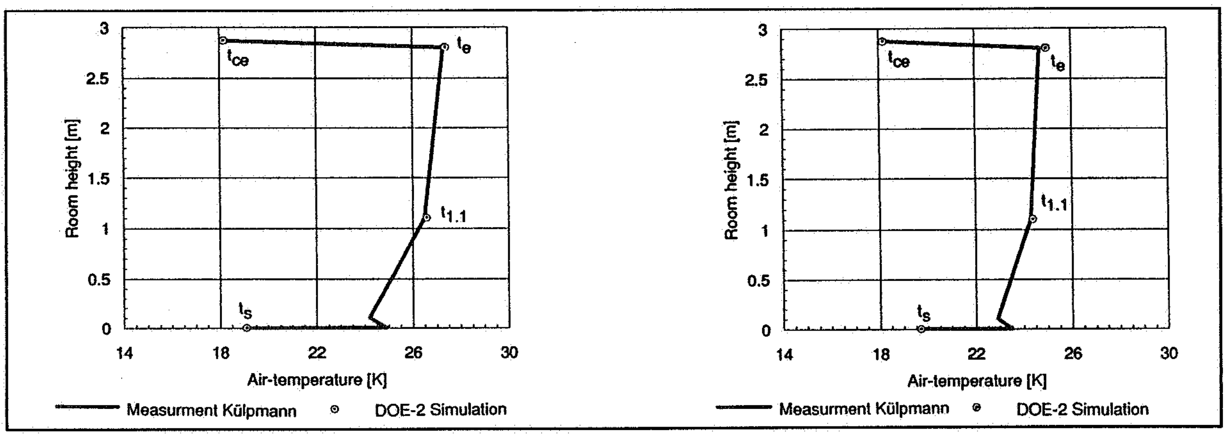


Figure 16: Comparison of DOE-2 calculation results with the measured data from experiment # 12 and 15, Kuelpmann

From figure 16 a good agreement of the DOE-2 simulation results with the measurements is recognised.

CONCLUSION

With the parameters from the detailed TRNSYS model, displacement ventilations and radiant cooling systems can also be simulated with DOE-2. The TRNSYS model was compared with instationary measurement data for displacement ventilation and radiant ceilings. A good agreement is shown. The same is true for the DOE-2 model of the displacement ventilation. The DOE-2 model for the radiant ceiling was compared to steady state measurement data from Kuelpmann. In the frame of a current Swiss project the dynamic case will be evaluated. More details about the models can be taken from [3,4,5].

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