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Simulation and Control of One-room Heating, Ventilation and Air-conditioning System

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Abstract

In the present study, a practical model of one-room thermodynamic behavior is proposed handling different dynamic modes of operation of air-conditioner and the corresponding adapted controllers. The developed model is based on the algorithm of Van Schijndel coupling the CFD modelling with SimuLink environment. A S-function block has been programmed which provides 5 input entities and 8 output entities to the S-function block thus simulating conditions close to the practice including unavoidable perturbation and constituting a MIMO system. The optimal position of the sensor has been achieved and the corresponding characteristics and optimal performance of standard PID/PI controller have been tuned in attempt to reach maximum comfort and cost effective conditions.

Keywords: *CFD, airflow dynamics, S-function block, SimuLink, MIMO, controllers.*

Introduction

The CFD modelling of the airflow and temperature pattern and distribution in a one-room has been strongly motivated by the strategy of building energy saving and to provide maximum comfort in terms of uniform temperature, air velocity and relative humidity (McBee 2011).

The implementation of CFD modelling to the control design is another contemporary approach since it is important to understand the dynamics of the controlled heating, cooling and air circulation in a one-room. Van Schijndel (2005, 2007, 2009) has developed algorithm for integration of CFD modelling based on commercial software COMSOL with SimuLink environment. The incorporation of the model into a S-function block of SimuLink provides engineers with the flexibility and comfort to concentrate on the control system performance and design having full visual monitoring on the thermodynamic behavior of the system in terms of video-image, video-animation as well as any parameter profile section of interest. The approach of Van Schijndel reveals feasibility of developing practical models of new systems as well as implementation of new controllers.

In the presented study, a practical model is proposed handling different modes of operation of air-conditioner and the corresponding adapted controllers.

Airflow Model and Numerical Procedure

Following van Schijndel (2005), Sinha (2000), and Sinha (2010), a transient buoyant warm jet in an empty single room is simulated. The model is described by two-dimensional incompressible flow using Boussinesq approximation with constant Reynolds and Grasshof numbers correspondingly Re = 1,000, Gr = 1e5, Pr = 0.71. The system of governing partial differential equations comprises the Navier-Stokes equations: *u*-momentum Eq. (1), *v*-momentum Eq. (2), continuity Eq. (3) and the energy Eq. (4), all in dimensionless form:

$$\frac{\partial u}{\partial t} = -\frac{\partial (uu)}{\partial x} - \frac{\partial (vu)}{\partial y} - \frac{\partial p}{\partial x} + \frac{1}{\mathrm{Re}}\nabla^2 u , \qquad (1)$$

$$\frac{\partial v}{\partial t} = -\frac{\partial (uv)}{\partial x} - \frac{\partial (vv)}{\partial y} - \frac{\partial p}{\partial y} + \frac{1}{\mathrm{Re}}\nabla^2 v + \frac{Gr}{\mathrm{Re}^2} T , \qquad (2)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 , \qquad (3)$$

and

$$\frac{\partial T}{\partial t} = -\frac{\partial (uT)}{\partial x} - \frac{\partial (vT)}{\partial y} + \frac{1}{\mathrm{Re\,Pr}}\nabla^2 T . \qquad (4)$$

Five Dirichlet boundary type heating and cooling sources are assumed for controlled heating and cooling inputs along with the uncontrolled perturbations. The geometry and the boundary conditions are presented in Fig. 1. Heat generation sources inside have not been considered.

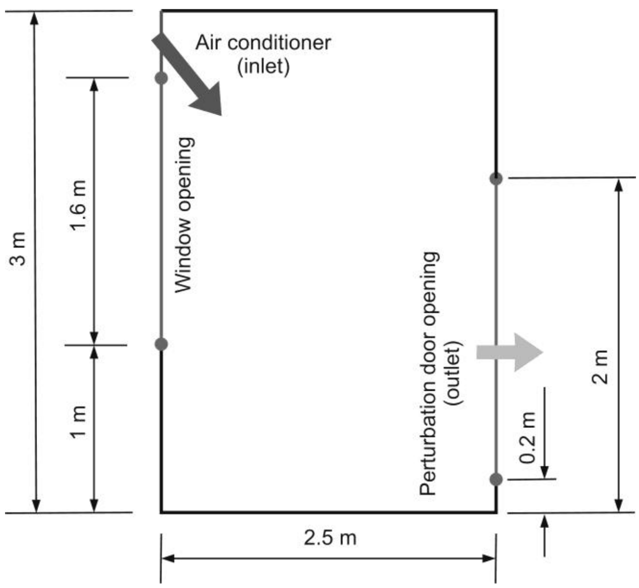

Fig. 1. Geometry of the problem.

The Comsol airflow model is implemented as a discrete m-file SimuLink S-function based on the analysis of (van Schijndel 2005). The original S-function of van Schijndel has been modified in order to meet more controlling boundary conditions, thus enabling the use of MIMO system. The following five S-block input entities have been provided to the model:

entity 1 - dimensionless temperature of the warm jet;

entity 2 - dimensionless inflow of the warm jet;

entity 3 - dimensionless perturbation impulses, simulating a door opening;

entity 4 – angle (in Radiant) of the air inflow, simulating the airflow direction control; and

entity 5 - dimensionless perturbation temperature, simulating a window opening.

Correspondingly, eight S-block output entities have been provided to the model:

entities 1 - 4 dimensionless temperatures of four sensors at different positions; and

entities 5 - 8 dimensionless readings of four airflow sensors at different positions.

The temperature has been normalized in the region between 18° - 45°C correspondingly between 0 - 1 in dimensionless units. All side-walls maintain constant cold temperature of 0 (18°C). The maximal temperature of the inlet flow is correspondingly 1 (45°C).

The inlet flow value has been used to normalize the flow correspondingly in the model.

Results

Recirculation Pattern

In most of the air conditioners, the airflow direction is under control by swinging louver up and down in a certain angle range. The instantaneous recirculation airflow isotherm and the streamline plots for an angle of 60° are presented in Fig. 2 and Fig. 3, respectively, 400 s after starting the simulation. The primary warm jet coming from the inlet in the upper left quarter of the room travels to the opposite wall and splits upward as well as downward thus forming two recirculation cells. The upper cell is counter clockwise and the cell below the main stream is clockwise. Generally, the isotherm pattern follows the streamline pattern due to the entrainment thus forming two well distinguished uniform temperature areas.

Moreover, a stagnant zone is observed in the lower left quarter of the room with lower temperature than in the recirculation cells.

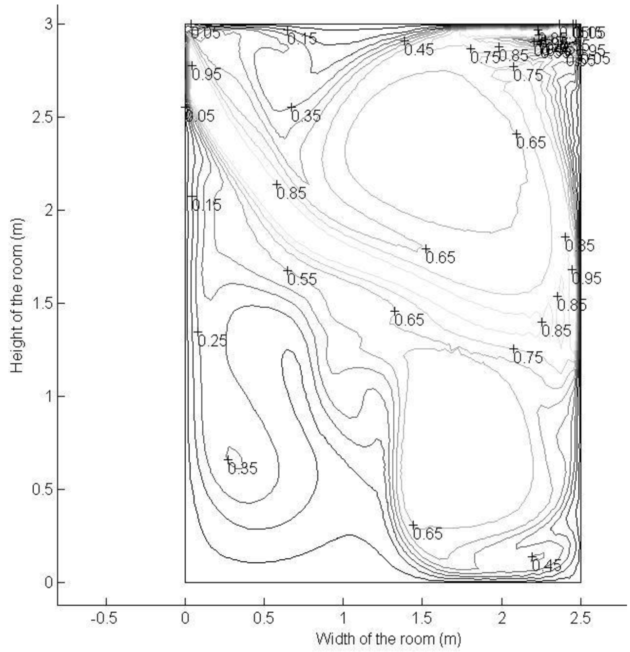

Fig. 2. Contour isotherms.

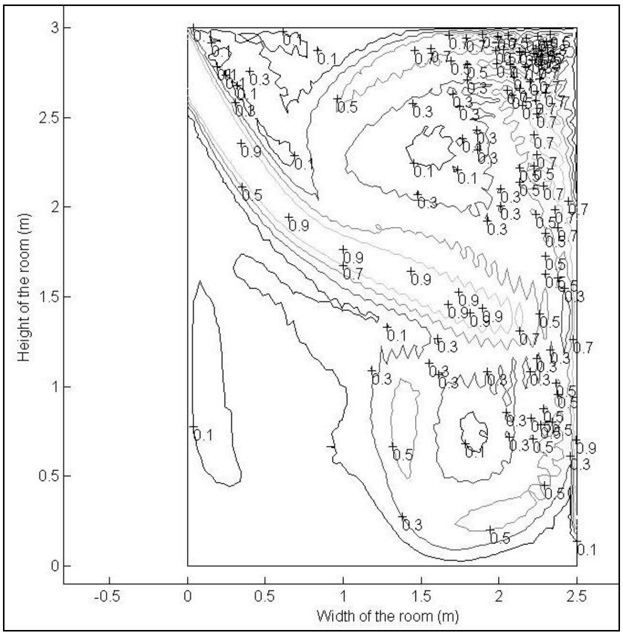

Fig. 3. Contour flow.

As a whole, the temperature in the room is not uniform in the four quarters as it is seen in Fig. 4 and Fig. 5, respectively. Also, the main jet stream is blowing strongly in the middle range of the room thus the requirement for maximum comfort is not met. The control is not effective in most of the ranges and the energy saving strategy is also problematic in this mode of operation.

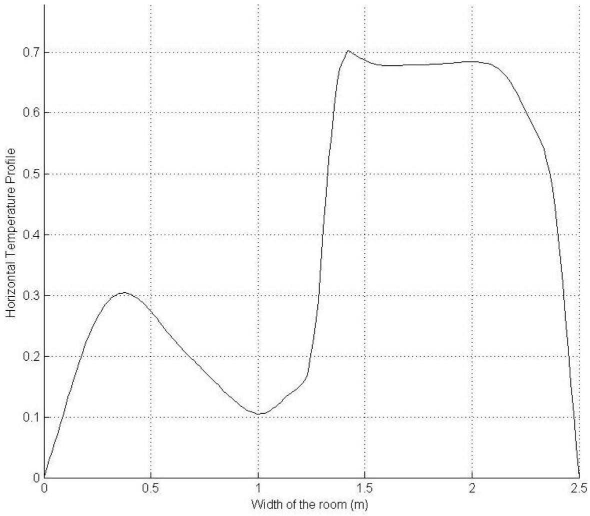

Fig. 4. Horizontal Temperature Profile at y = 0.5.

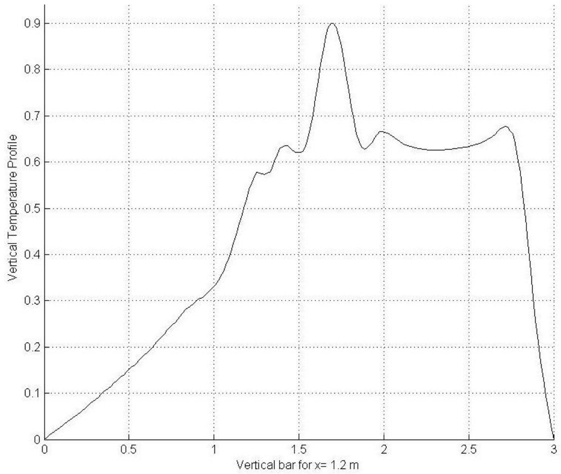

Fig. 5. Vertical temperature profile for x = 0.5.

In pursuance of maximum comfort and reliable control performance, the angle sweep range between 50° and 85° has been simulated. Increasing the angle, the extent of the upper recirculation cell increases, while the lower recirculation cell reduces. At an angle of 80° only one single recirculation cell is observed as it is seen in Fig. 6 and Fig. 7 for 200 s after starting the simulation.

The horizontal (at level y = 0.5 m) temperature profile is presented in Fig. 8. The vertical (at level x = 1.2 m) temperature profile is presented in Fig. 9, respectively.

In both cases, a good uniform temperature distribution is observed in the whole recirculation cell. Moreover the velocity of the flow also meets the requirement for maximum comfort.

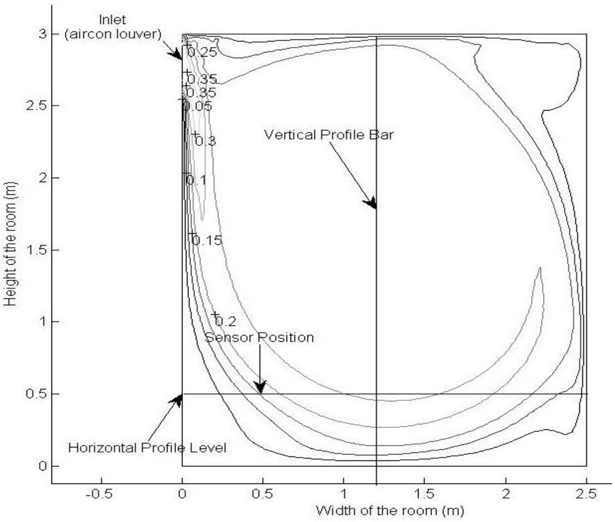

Fig. 6. Contour isotherms.

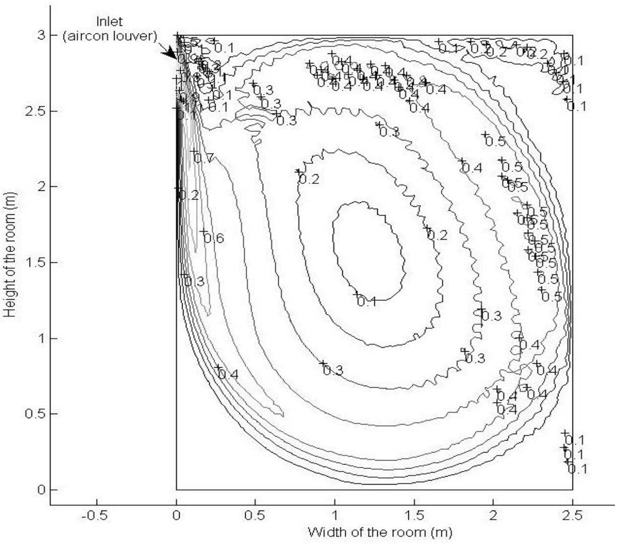

Fig. 7. Contour flow streamline.

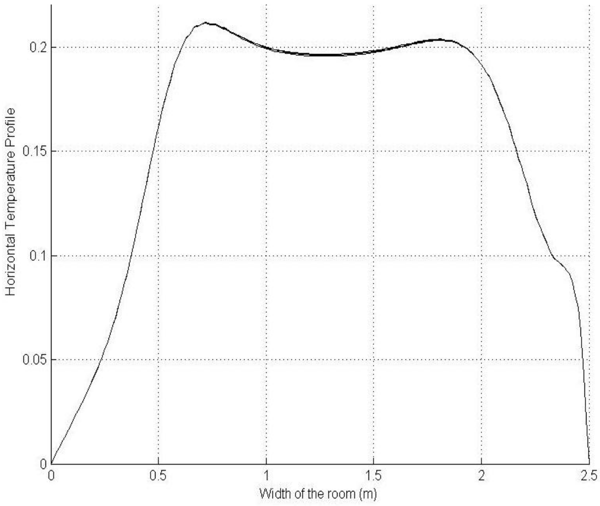

Fig. 8. Horizontal temperature profile at y = 0.5.

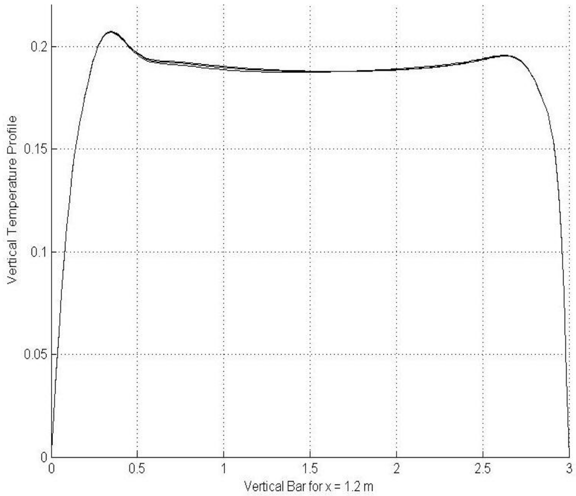

Fig. 9. Vertical Temperature Profile for x = 1.2 m.

Control System and Sensor Position

A standard PI/PID controller has been implemented for the temperature control in the room. The corresponding SimuLink model including the PI/PID controller as well as the S-function block is presented in Fig. 10. The controllers have been tuned according to the standard method of Ziegler-Nichols.

The results for the response of the thermodynamic system and the control signal are presented in Figs. 11-14 for different position of the temperature sensor in the room at level 0.5 m above the floor. As indicated in Fig. 6, the position of the sensor has been swept all the way between the left wall and the right wall. Fig. 11 presents the case when the sensor is positioned close to the left wall (0.4 m off the left wall).

A control signal of level of 0.45 is observed as well as a settling time of 200 s. The same operating parameters are observed after exciting the system by perturbation impulses of period of 250 s (10% duty cycle). Despite the stable performance of the controller and the satisfactorily short settling time, the level of 0.45 is not acceptable from energy saving strategy point of view. This disadvantage is due to the small stagnant zone observable in the left lower edge of the room, which needs more energy. The optimal performance of the controller has been achieved for sensor position of 0.5 - 0.6 m off the left wall when the control signal level is about 0.35 (see Fig. 12).

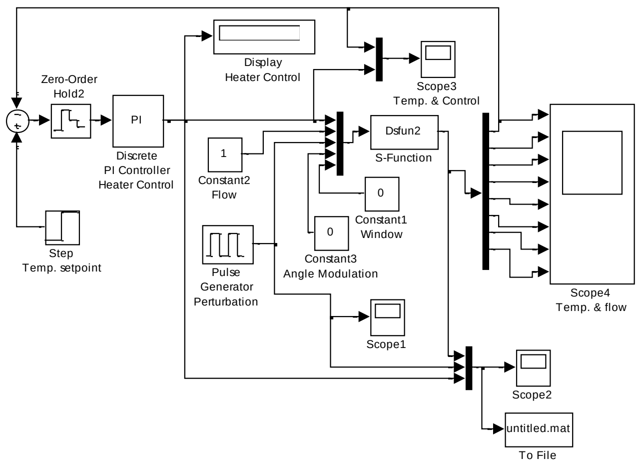

Fig. 10. S-function block.

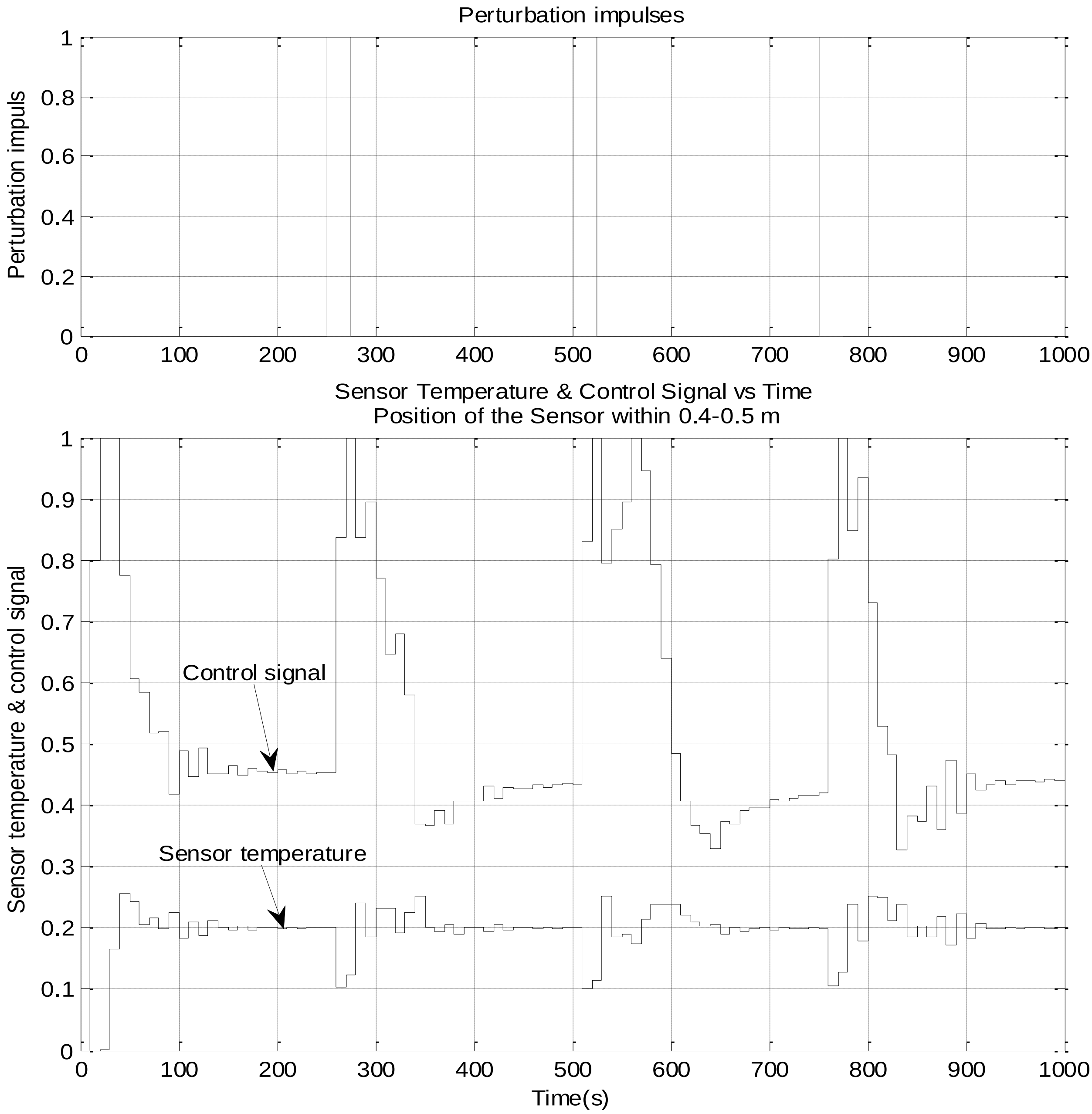

Fig. 11. Temperature, control and perturbation signals within 0.4 - 0.5 m.

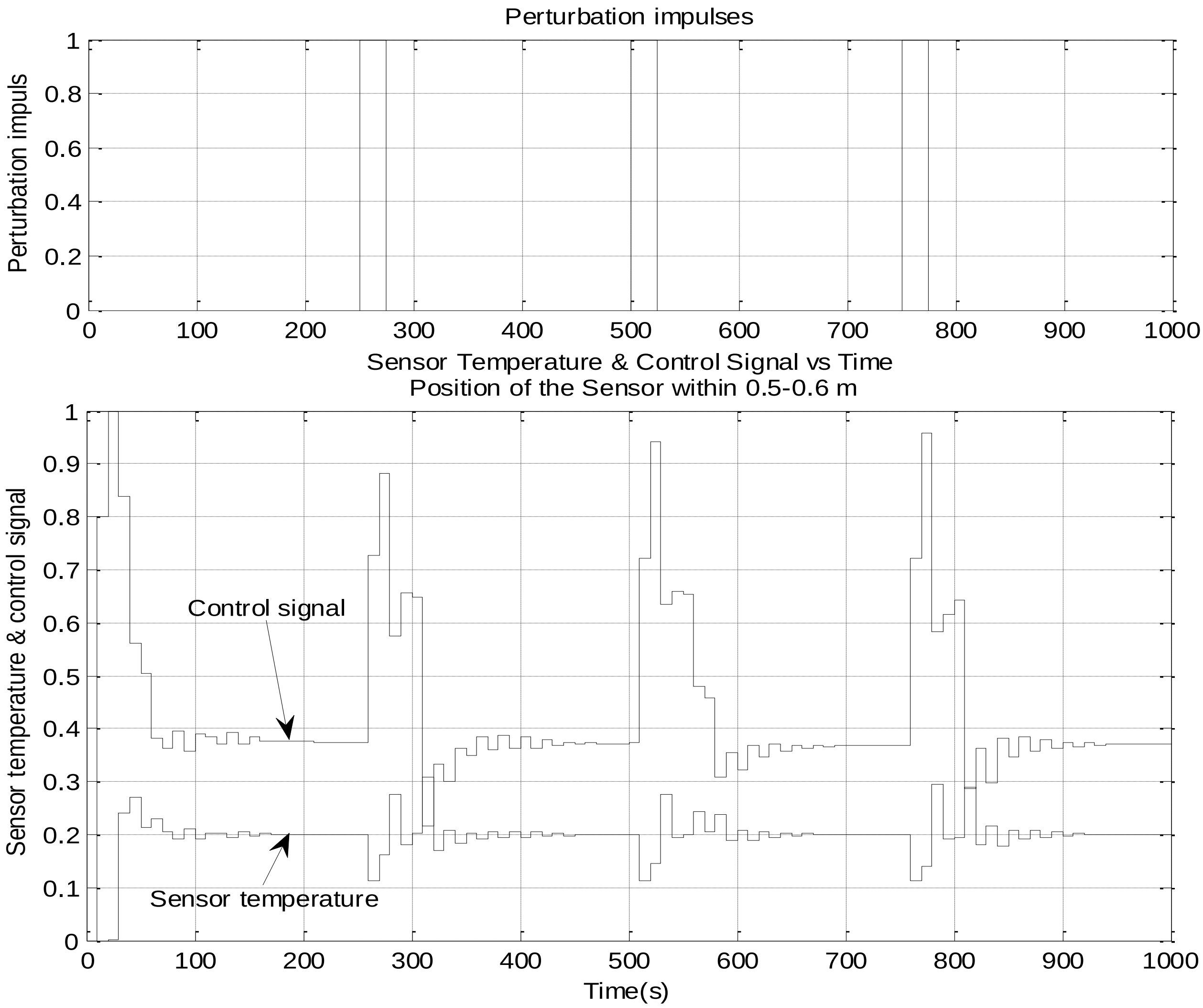

Fig. 12. Temperature, control and perturbation signals within 0.5 - 0.6 m.

Further shift of the sensor toward the right wall locates the sensor in the recirculation cell. Despite of the controller settings, the system is underdamped, the control signal level is unacceptably high from energy saving point of view and the wind-up of the control signal is also unacceptable as it is seen in Fig. 13. This unstable performance of the controller is due to the extended time delay needed for the warm jet to reach the sensor following the complicated stream trajectory and corresponding entrainment.

Fig. 14 shows the response of the system when the sensor is positioned 1.8-1.9 m off the left wall. The performance of the controller is close to the optimal case of 0.5 - 0.6 m which is due to the mirror symmetry of the main stream. Still the wind-up of the control signal is relative high in comparison with the optimal case in Fig. 12.

Conclusion

In the present study, a practical model is proposed handling different modes of operation of air-conditioner and the corresponding adapted controllers. The developed model is based on the algorithm of Van Schijndel coupling the CFD modelling with SimuLink environment. The thermodynamic behavior of closed one-room is investigated under different angle range of the louvers between 50° and 85°. Two different modes of the air conditioner operation have been observed.

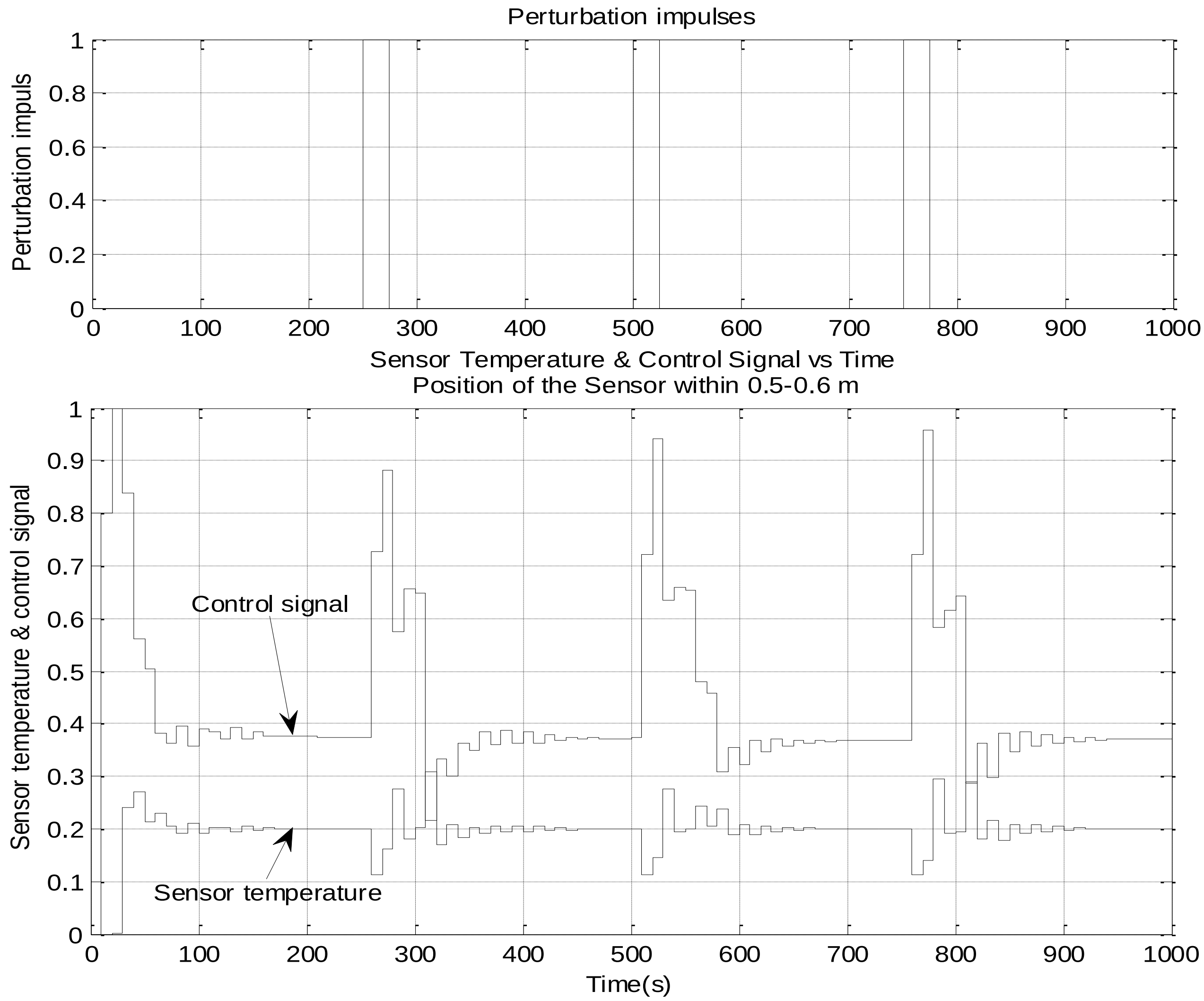

Fig. 13. Temperature, control and perturbation signals within 1.0 - 1.1 m.

Under angles smaller than 80° two recirculation cells arise and the domain splits into four different sub-domains: two of them being recirculation cells with different temperatures, one input sub-domain with strong warm jet crossing whole room and one quarter of stagnancy, where the temperature is cost ineffective to be increased and controlled.

Optimal results have been achieved at angle of 80°. One single large recirculation cell has been observed, embracing quite whole room and revealing uniform temperature field, which is under effective temperature control even based on the standard PID/PI controllers (see Figs. A1 and A2 in the Appendix). The developed practical model provides 5 input entities and 8 output entities to the S-function block thus constituting a MIMO system. All input entities enable full control actuation on the thermodynamic system simulating conditions close to the practice including unavoidable perturbation. The output entities simulate the readings of 8 sensors for temperature as well for flow located at different positions in the domain. The optimal position of the sensor has been achieved and the corresponding characteristics and optimal performance of the PID/PI controller have been tuned. A further research however is needed in order to adapt to the model more advanced controllers, revealing in full scale the possibilities of the MIMO system and investigating more complicated one-room model with internal obstacles.

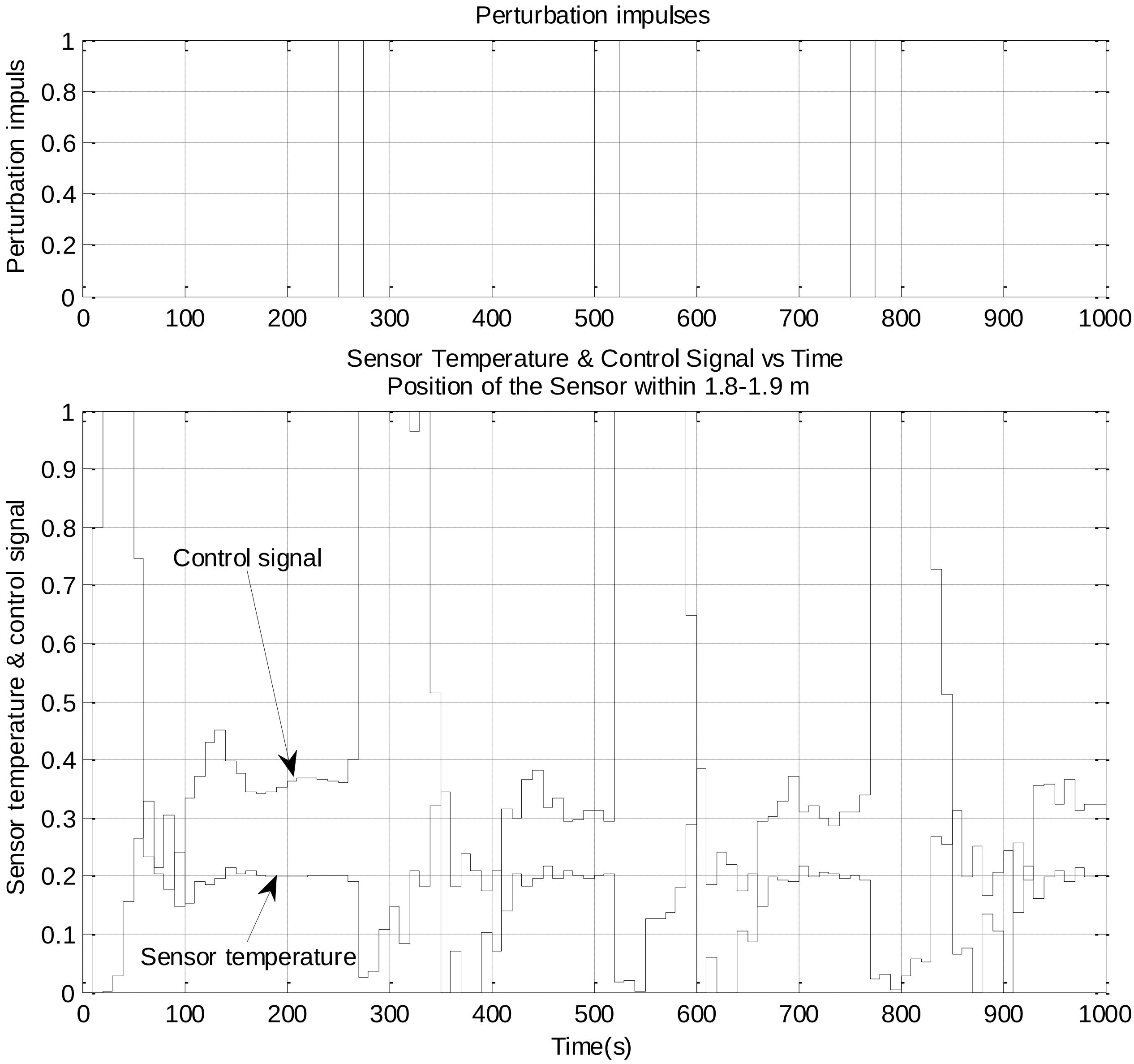

Fig. 14. Temperature, control and perturbation signals within 1.8 - 1.9 m.

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Appendix

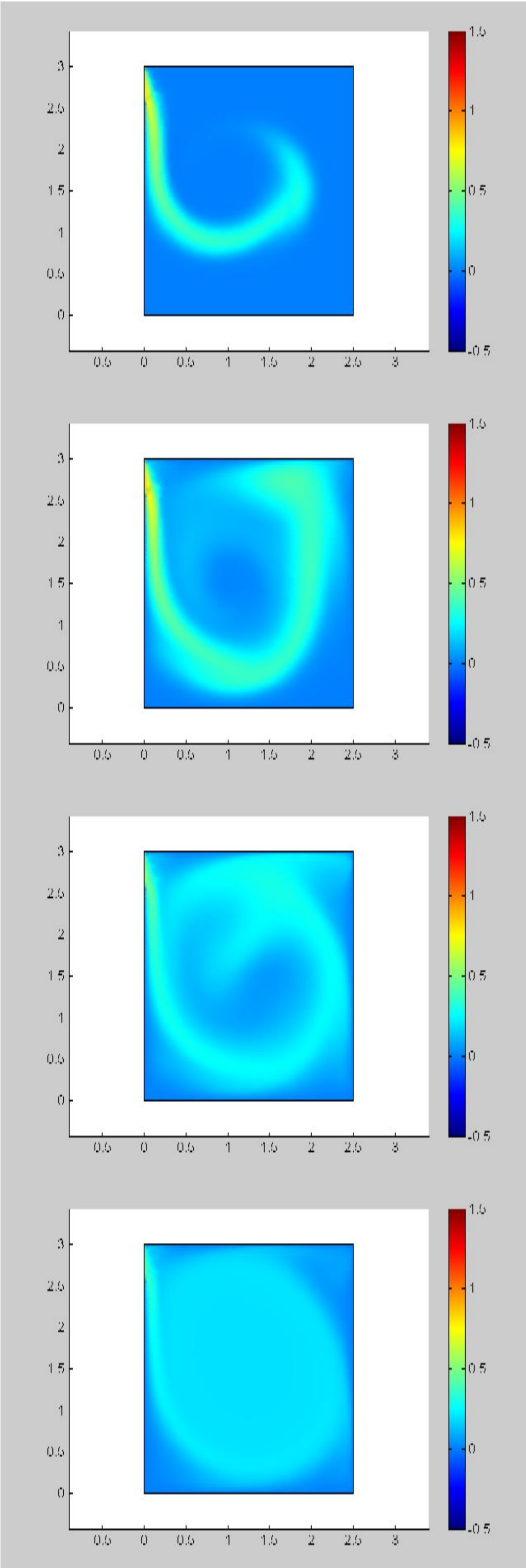

Fig. A1. Time evolution of temperature field. Last image: full uniform temperature field after settling time of 200 s of the controller.

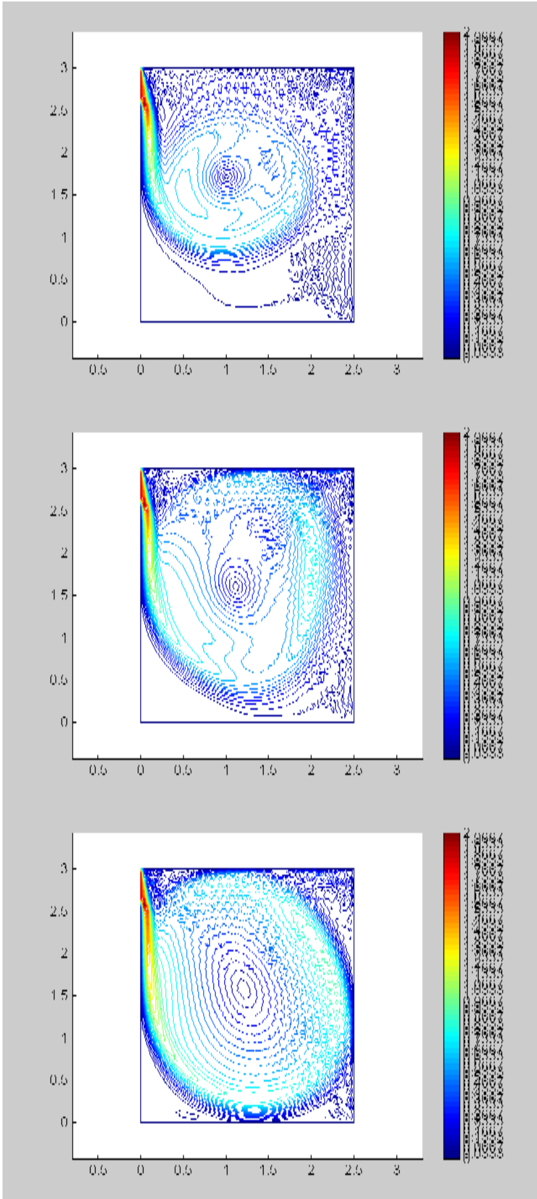

Fig. A2. Time evolution of the velocity field.

Note: Full video is available at <www.phys.tu-sofia.bg>.