



## **SIMULATING THE EFFECT OF COMPLEX INDOOR ENVIRONMENTAL CONDITIONS ON HUMAN THERMAL COMFORT**

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### **ABSTRACT**

This paper describes the methods developed to couple a commercial CFD program with a multi-segmented model of human thermal comfort and physiology.

A CFD model is able to predict detailed temperatures and velocities of airflow around a human body, whilst a thermal comfort model is able to predict the response of a human to the environment surrounding it. By coupling the two models and exchanging information about the heat exchange at the body surface the coupled system can potentially predict the response of a human body to detailed local environmental conditions.

This paper presents a method of exchanging data, using shared files, to provide a means of dynamically exchanging simulation data with the IESD-Fiala model during the CFD solution process. Additional code is used to set boundary conditions for the CFD simulation at the body surface as determined by the IESD-Fiala model and to return information about local environmental conditions adjacent to the body surface as determined by the CFD simulation.

Keywords: CFD; thermal comfort; model coupling

### **INTRODUCTION**

In an attempt to provide a comfortable environment for the occupants whilst at the same time reducing energy consumption, building designers are increasingly making use of natural ventilation as an alternative to air conditioning in non-domestic buildings. By its nature, natural ventilation is less tightly controlled when compared to air conditioning, and computer modelling is often used to predict the likely performance of a building design. Computational Fluid Dynamics (CFD) is a computer modelling technique that is able to predict in considerable detail complex patterns of airflow and air temperature distribution. It has been used successfully to predict the likely ventilation performance of many advanced naturally ventilated buildings (e.g. Cook and Short 2005, Short and Cook 2005). In design practice simple shaped blocks are often used to represent human occupants in CFD models and derive empirically-based thermal comfort parameters such as PMV and PPD.

A multi-segmented human thermal comfort model (the IESD-Fiala model) has been developed that can

predict the response of the human body to varying environmental conditions and can predict the resulting degree of comfort or discomfort a person experiences (Fiala et al 2003). It has been extensively validated across a wide range of steady and transient indoor and outdoor environmental conditions. The IESD-Fiala model uses environmental parameters, such as the temperature, humidity and velocity of air at the skin surface, to predict the response of the human thermoregulatory system to these external stimuli over a period of time.

The aim of this research is to use a commercial CFD model to predict the local environmental conditions around a human body and to use the IESD-Fiala model to predict the response of the human body to those conditions, both the degree of comfort or discomfort experienced and temperature changes at the body surface. Changes in temperature at the body surface are also fed back to the CFD model to enable the effect that the body has on the local environment to be taken into account. This two-way data transfer is thought to be particularly important when modelling naturally ventilated spaces where air velocities are low, due to the small driving forces. In such cases, the effect that a human body has on the local environment is potentially more significant than in other environments where velocities are higher.

Various degrees of coupling systems have been reported. For example Murakami et al. (2000) and Al-Mogbel (2003) used a simplified shape to represent a human body in CFD and coupled this with a two-node thermal regulatory model (Gagge et al 1986). Tanabe et al. (2002) integrated a 65-node human thermoregulatory model with a 3D model of a nude male body in CFD which incorporated radiation heat transfer. Similarly, Omori et al (2004) coupled a realistic nude female body with a PMV model (Fanger, 1970). Streblow et al (2008) coupled a 16-segment Tanabe model with CFD. Van Treeck et al (2008) also propose to couple CFD with the Fiala model. This research considers more realistic, clothed bodies in representative typical indoor environments. The research project uses CFD techniques to predict local environmental parameters for 59 regions of the human body, to dynamically exchange those parameters with the IESD-Fiala model to enable human thermal comfort to be predicted along with the effect the body has on its surroundings and to enable building designers to directly assess the impact of design decisions on

occupant comfort. Consequently, a better understanding and innovative control strategies of indoor environments could be developed, providing effective design tools to improve building thermal performance, improve occupant comfort and reduce energy consumption.

This paper describes a new coupled system of integrating CFD with the IESD-Fiala model. The system is designed using user subroutines to interact with the CFD solver. The intention is that the techniques developed will be applicable to any CFD platform which offers user-accessible development tools. The coupled system is demonstrated by modelling a person standing in a naturally ventilated environment. The resulting body surface temperatures, air temperatures and air velocities that result are presented.

### **THERMAL COMFORT MODEL**

The IESD-Fiala thermal comfort model consists of two interacting systems: the controlling active system; and the controlled passive system. The active system (Fiala et al 2001) is a cybernetic model predicting the thermoregulatory defence reactions of the central nervous system. The passive system (Fiala et al 1999) simulates the physical human body and the dynamic heat transfer phenomena that occur inside the body and at its surface.

The IESD-Fiala model represents an average person with a body weight of 73.5 kg, body fat content of 14%wt, Dubois-area of 1.86 m<sup>2</sup>, basal metabolism of 87 W, basal evaporation from the skin of 18W, and basal cardiac output of 4.9 L/min.

#### **Active system**

The active system controls the response of the body to the local environment, to maintain its internal temperature at a fairly constant value, using four essential thermoregulatory responses; vasoconstriction, vasodilatation, shivering and sweating. Peripheral vasomotion, via suppression (vasoconstriction) and elevation (vasodilatation) of the skin blood flow, is activated to regulate internal temperature in moderate environments. In cold conditions, vasoconstriction is accompanied by shivering, i.e. a regulatory increase in the metabolic heat generation by contraction of muscle fibres. In warm and hot conditions, vasodilatation is accompanied by sweating, i.e. excretion of moisture at the skin which evaporates cooling the body.

#### **Passive system**

The passive system is a multi-segmental, multi-layered representation of the human body with spatial subdivisions and detailed information about anatomic and geometrical body properties. The body is idealised as 19 spherical and cylindrical elements which are further subdivided into spatial sectors to give a total of 59 body parts. The sizes and composition of the 19 body elements and the thermal characteristics of clothing covering those elements can be changed to represent different geometric body characteristics and different clothing levels.

#### **Environmental heat exchange**

The IESD-Fiala model predicts the response of the human body to the local environmental conditions surrounding the body via the convective, radiative and conductive heat exchange at the body surface. In this research a CFD model is used to predict the convective heat flux and the long-wave radiative heat flux at the skin surface. In response the IESD-Fiala model predicts the body surface temperature and evaporative heat loss flux resulting from the evaporation of moisture on the skin surface (sweating). During this ongoing research it is anticipated that the data exchanged will be extended to include the parameters required to calculate the effect of short-wave irradiation.

#### **IESD-Fiala model convergence**

In its stand-alone mode of operation, the IESD-Fiala model is able to predict the body's response to local environmental conditions that change over time, i.e. transient conditions. In this research, the coupled system models the interaction between the body and the local environment under steady-state conditions. The IESD-Fiala model is therefore run in a way that corresponds to the body being exposed to the same local conditions for a long period of time to ensure that the model reaches a steady state. In this way the IESD-Fiala model achieves internal convergence each time it is run.

### **REVISED BODY GEOMETRY**

In this research, the idealised body geometry described above is replaced by a more realistic three-dimensional representation of a clothed human body, termed a computational thermal manikin (CTM) (Yang et al 2007), with a surface area of 2.019m<sup>2</sup>. The manikin, illustrated in Figure 1, represents a casually dressed typical male with a height of 1.73m. The manikin geometry has been optimised, particularly in areas such as the hands, the armpits and the crotch, to allow a CFD mesh to be constructed around it.

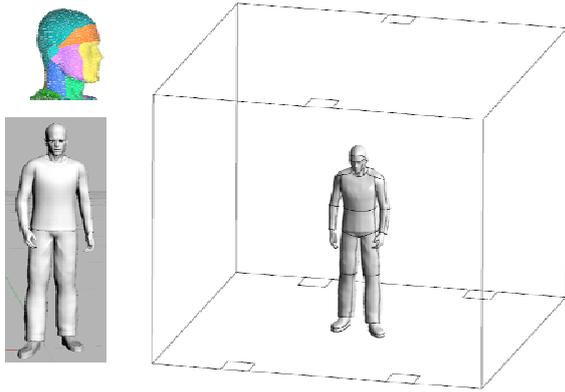


Figure 1 A clothed computational thermal manikin in a naturally ventilated room, with upper and lower openings.

Two body geometries have been produced representing a nude figure and a clothed figure, having 56,000 and 65,000 surface nodes respectively.

### **CFD MODEL**

The commercial CFD code ANSYS CFX (ANSYS, 2007), version 11, is used to model air flow and heat transfer in this work. Steady-state simulations have been used to model the thermal conditions in an indoor environment with a human body as the only heat source. The software employs a coupled, fully implicit solver using a transient evolution of the flow from the initial conditions. The physical timesteps used in the transient evolution provide a means of controlling the solution procedure. CFX uses a multi-element type mesh comprising hexahedrals, tetrahedrals, wedges and pyramids. The conservation equations are solved using the Finite Volume method (Versteeg and Malalasekera 1995). Flow variables (velocity, pressure, enthalpy, etc) are defined at the corners of each element which are located at the centre of each control volume used for solving the conservation equations. Solver convergence is deemed to have been achieved when the normalised residual values at the end of an outer iteration fall below a level specified by the user, usually  $1.0e-04$  or  $1.0e-05$ .

### **ANSYS CFX solver customisation**

One reason for choosing ANSYS CFX for this project is that it provides a powerful Application Program Interface (API). In this research this feature is used to change the body surface temperatures and moisture during the solution cycle predicted by the IESD-Fiala model. CFX provides a range of customisation options.

### **CFX Command Language (CCL)**

CFX Command Language (CCL) defines the controlling parameters for the simulation. In addition to standard parameters, such as the simulation boundary conditions specified by the user when setting-up the simulation, user defined values can also be specified. In this project, fixed values used to control the coupled simulation are specified in the CCL.

### **CFX Expression Language (CEL)**

CFX Expression Language (CEL) is an interpreted, declarative language which can be used within the CCL to control the simulation. For example, CEL enables mathematical expressions to be used in place of fixed values within the CCL. CEL has access to many CFX solver internal variables. Where standard CEL functions are not sufficient, additional CEL functions can be written in FORTRAN. In this project, CEL functions written in FORTRAN are used to set the surface temperature and moisture for each body part. As the simulation progresses the custom CEL functions provide updated values provided by the IESD-Fiala model.

### **Embedded Perl**

More sophisticated customisation can be achieved through the use of embedded Perl. Embedded Perl adds facilities to CCL such as loops, if/then/else constructs, subroutines and other common programming features. Embedded Perl can be used to implement repetitive tasks both within the solver CCL and post processing.

### **User FORTRAN**

The most sophisticated customisation can be achieved using what is termed Junction Box code. Junction Box code, written in FORTRAN, provides very powerful and versatile facilities for customisation. In addition to the full range of programming facilities provided by the FORTRAN language, a CFX library of functions provides full access to all solver data structures, subroutines, functions and access to all data via the CFX Memory Management System. Junction Box routines are called at specific points in the execution cycle as specified in the CCL. The events relevant to steady-state simulations are illustrated in figure 2. In this project, Junction Box code is used to control the coupled simulation and to control the exchange of data between the CFX solver and the IESD-Fiala model, supplying updated temperature and moisture values from the IESD-Fiala model to the custom CEL functions and returning convective and radiative heat flux values to the IESD-Fiala model.

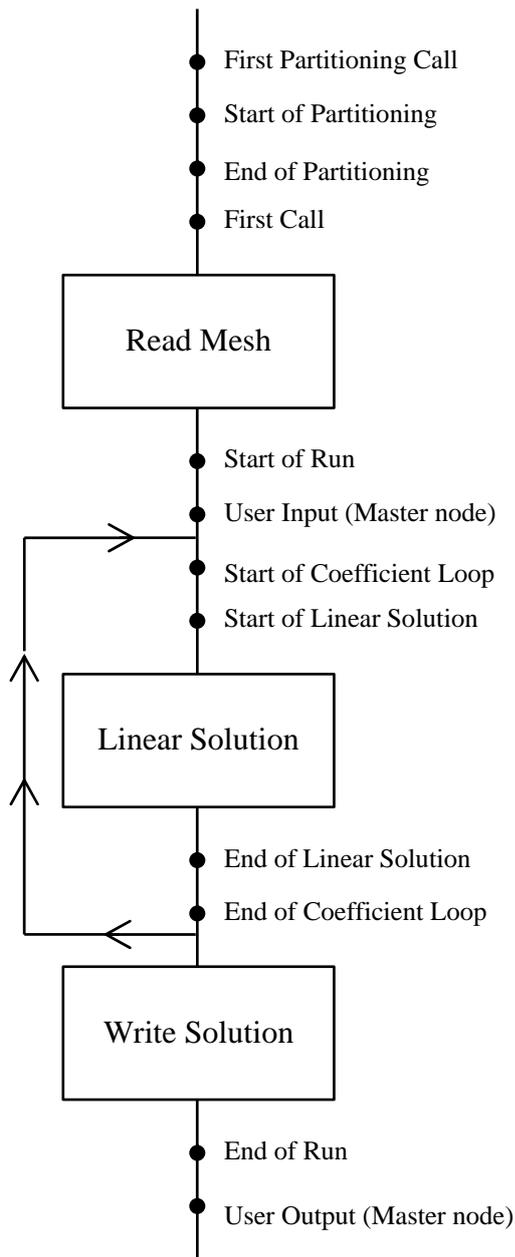


Figure 2, Points within the CFD solver process where junction box routines can be called

### **SIMULATION**

In the coupled simulation, the CFD model predicts both the local environmental conditions surrounding the human body and the effect the warm body has on that local environment. The IESD-Fiala model predicts the body's response to the local environment at the body surface. As the predictions of each model have an effect on the predictions of the other, the coupled simulation, illustrated in figure 3, is an iterative process in which the two models attempt to arrive at a consensus.

### **Data exchange**

Two methods of exchanging data between the models were considered; network sockets and data files. A network socket, identified by a unique (socket)

number, provides a dedicated channel of communication between two computers connected via a computer network. The use of network sockets is an appropriate technique when the two computer models are to be run on different computer systems. This method has previously been successfully used to couple the IESD-Fiala model with the INKA car simulator (Fiala et al 2004). In this research the IESD-Fiala model and the CFD solver run on the same computer system. A simple approach using locally stored files is therefore employed.

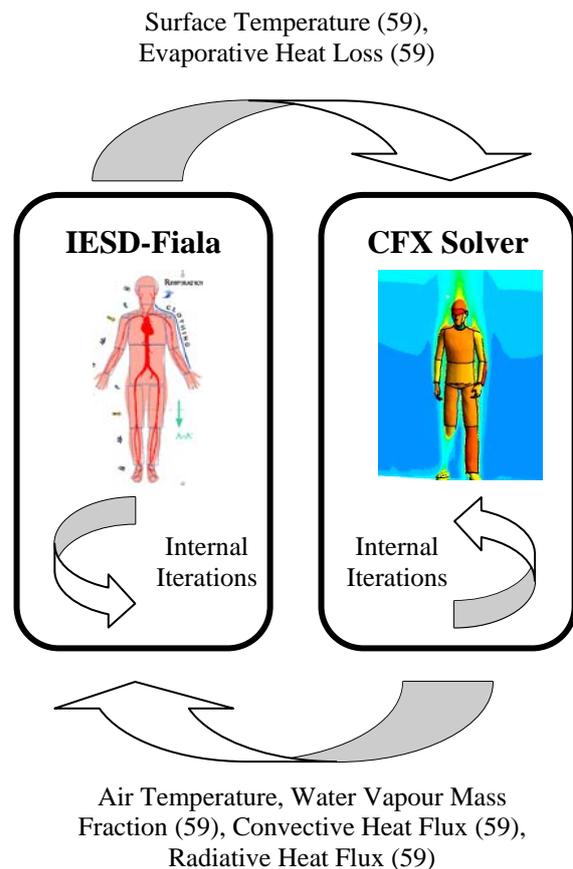


Figure 3, the model data exchange process

### **The coupling algorithm**

At the beginning of the coupled simulation, the IESD-Fiala model is run to provide an initial set of boundary conditions at the body surface, based on an initial set of environmental conditions. The body surface temperatures and local evaporative heat losses for each of the 59 body parts predicted by the initial simulation are written to a data file to be used as boundary conditions by the CFD simulation. The CFD solver is then run.

Triggered by the *User Input* solver event (see Figure 2), a Junction Box routine reads the boundary condition data into tables in the CFX Memory Management System. CEL functions (written in FORTRAN), specified in place of fixed values in the CCL, then provide values from these tables whenever

required by the solver. The solver runs until a predefined degree of convergence is achieved, i.e. when the RMS residual values have fallen below a pre-set threshold value (provided in the CCL), as determined by a further Junction Box routine trigger by the *End of Coefficient Loop* solver event. The volume averaged air temperature (room temperature) and moisture mass fraction are then written to a data file, along with the convective and radiative heat flux for each of the 59 body parts, to provide a new set of environmental conditions for the IESD-Fiala model. An empty file is also produced that acts as a signal to the IESD-Fiala model to indicate that new environmental data is available. The CFX solver then waits for the IESD-Fiala model.

When the IESD-Fiala model detects the signal file from the CFD solver it reads the environmental data file and performs a simulation to predict the body's response to these new conditions. When this is complete, the IESD-Fiala model writes a new set of body surface temperatures and local evaporative heat losses for each of the 59 body parts to a data file. Another empty file is then produced that acts as a signal to the CFX solver to indicate that a new set of boundary condition data is available.

When the CFX solver detects the signal file the new boundary condition data is loaded into the tables in the CFX Memory Management System and solving resumed. After a data exchange has taken place, the CFX solver is run for a minimum number of iterations (number provided in the CCL) before a further exchange is initiated, irrespective of the values of the residuals. This is to allow the CFD calculation process to stabilise following the change of boundary conditions.

The CFX solver and IESD-Fiala model continue to exchange data until the RMS residual values fall below a second pre-set threshold value (provided in the CCL). No data exchange takes place while the RMS residual values remain below this threshold. However, should any of the RMS residual values rise above the threshold as the CFD solution process continues, data will again be exchanged between the two models. Data exchange is also terminated if the difference in mean body surface temperature between consecutive data exchanges is less than 0.001°C. The CFX solver is then allowed to run without further data exchanges taking place until the desired level of CFD convergence is achieved.

## **DISCUSSION AND RESULTS**

The new coupled system has been used to model a standing nude male figure in a mechanically ventilated space with an air temperature of 21°C and a relative humidity of 50%. For accurate boundary layer computations, prism layers are placed near the manikin body and walls. The  $k-\omega$  based Shear Stress Transport (SST) turbulence model (Menter 1994) was used, the maximum value of  $y^+$  (the

dimensionless distance from the wall) was 1.8, with an average value of 1.3. A discrete transfer radiation model was used (ANSYS 2007) to model the long-wave radiation heat exchange between the body and surrounding surfaces.

The effect that changing body surface temperatures during the CFD simulation has on the RMS Energy Residual value can be seen in figure 4. Each spike in the light blue trace, beginning after all the RMS residual values have fallen below the upper threshold of 1.0e-03, shows where a data exchange between the two models has taken place. The reduction in the size of these spikes as the coupled simulation proceeds indicates that the coupled system is converging. In this example, approximately 60 data exchanges took place before the RMS residuals fell below the lower threshold of 1.0e-04. The CFD simulation then continued without further data exchange until approximately 4000 CFD iterations had been performed, with various physical time steps from max 5 [s] down to 0.25 [s], before the RMS residuals fell below 1.0e-5.

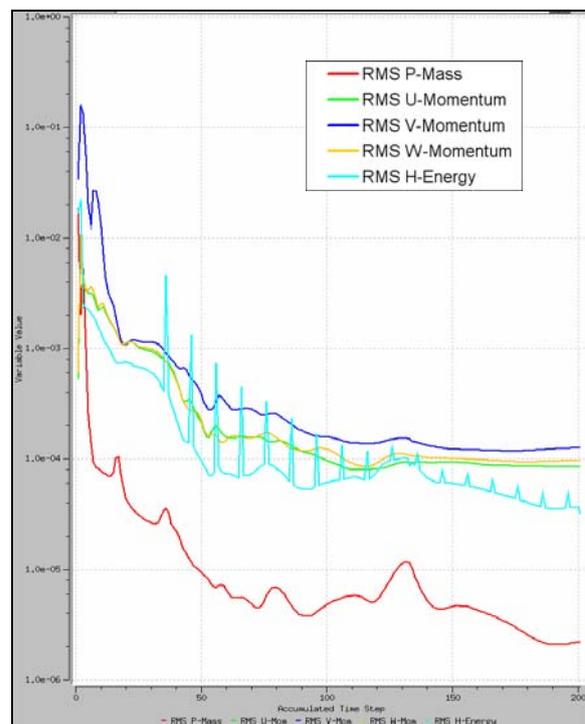


Figure 4 RMS Residual values during a coupled simulation

The simulation was carried out using a computer cluster consisting of 32 nodes each equipped with dual quad-core 'Harpertown' Xeon processors and 16 GB of RAM. In this example the simulation took 17.6 CPU hours using 16 processor cores.

Figure 5 shows the temperatures at the body surface predicted by the IESD-Fiala model. The effect this warm body has on the local environment is illustrated in figures 6 and 7.

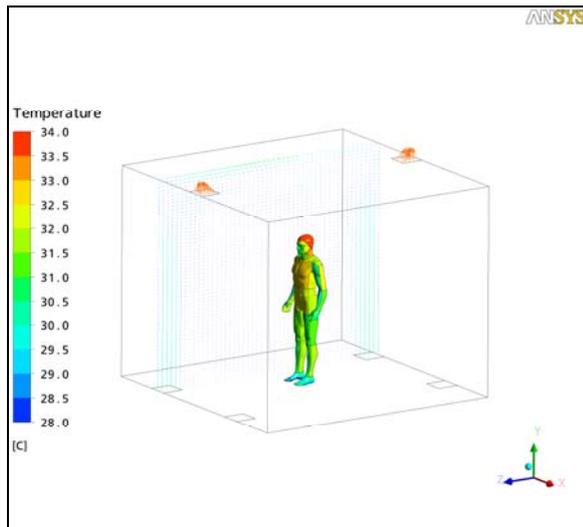


Figure 5 Mean surface temperatures for each body part predicted by the IESD-Fiala model

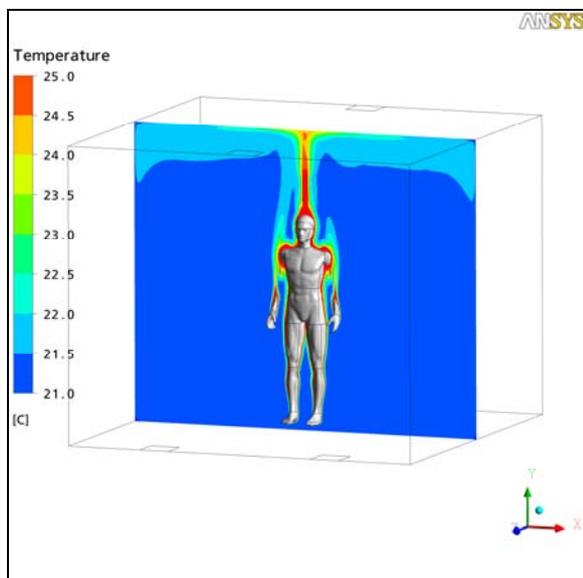


Figure 6 Predicted air temperatures around the body

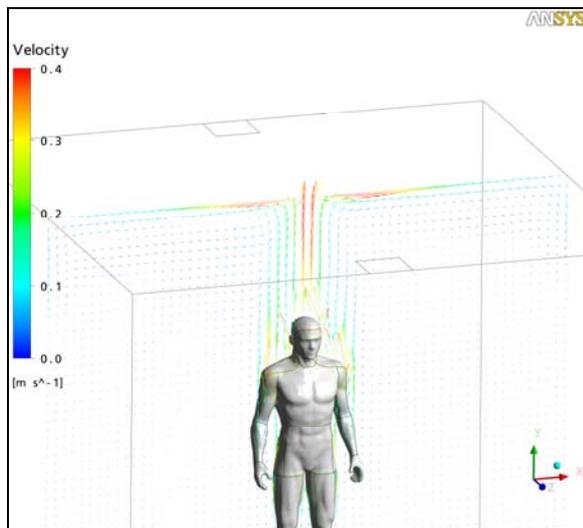


Figure 7 Velocity plot shows the thermal plume above the body

The example given in figure 5 to 7 describes the simulation of a nude figure. When simulating a fully clothed figure difficulties have been encountered obtaining good CFD convergence. This may be due to greater differences in the surface temperatures, resulting in a high temperature gradient between adjacent cells at the interface between body parts. This is thought to lead to greater instability within the CFD predictions resulting in greater fluctuations in body part temperatures predicted by the IESD-Fiala model following each data exchange. At the time of writing, methods to overcome this were under investigation.

## CONCLUSIONS

A new simulation system coupling CFD with a dynamic model of human thermoregulation and thermal comfort has been developed that is able to predict human thermal comfort in complex environmental conditions. However further work is required to improve the coupling algorithm to improve convergence, particularly when modelling clothed figures.

It is expected that this system will find application in a diverse range of environments, such as car, train and aircraft cabin design, as well as naturally ventilated building design.

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