EXPERIMENTAL AND NUMERICAL PREDICTION OF AIRFLOW IN A ROOM - LITERATURE SUMMARY

G.Pillutla[1], R. Mishra[1], S.M.Barrans[1] J.Barrans[2]
[1] University of Huddersfield, Queensgate, Huddersfield HD1 3DH, UK
[2] Heights – UK Limited, Halifax LS2 9JT, UK

ABSTRACT

This paper presents a review of literature pertaining to prediction of air flow in a room. The paper initially discusses various mathematical models adopted in previos studies and highlights the models best suited to evaluate heat transfer from a standalone water filled radiator heating system. The air flow equation accounting for forced and free convection used by computational systems is illustrated. Key parameters to be measured and used as boundary conditions are highlighted. Experimental methods and relevant systems and devices used to measure and quantify these have been summarized. An overview of the CFD (Computational Fluid Dynamics) models and comparative study has been done to establish the best way forward.

Keywords air flow, CFD

1 MATHEMATICAL EVALUATION

Air flow in a room is a very complex 3 dimensional turbulent flow. Furniture, number of exposed and unexposed walls, number of windows and location of heat source and ventilation ducts are some of the key factors influencing the flow. Over the years work has been done to understand the influence of each of these parameters for a given setup.

1.1 Heat Transfer Coefficient

1.1.1) Natural Convection:- As air or water is heated it changes its density. Natural convection is movement of fluid caused by difference in density in a given system. We experience wind and draft as a result of this thermal variation over the surface of the earth. The rate of heat transfer from a surface depends on the temperature gradient between the surface and the surrounding air, exposed area and the film coefficient. Heat transfer from the source due to convection is expressed by Newton's law of cooling in equation 1.

$$Q_{convective} = h_c A\left(T_S - T_a\right) \qquad (1)$$

Position of the hot source and the adjacent surfaces also influence the heat loss. Hence it is very important to understand the effect of the room surfaces along with the heat loss from the heat source.
Previous experimental and analytical work sited by Wallenten suggest that equation (2) holds good for laminar and turbulent flows over the room walls whereas equation (3) by Awbi et al also accounts for radiation of the surfaces in the room

$$h_{cn} = \left[\left(1.51\left(\frac{|\Delta T|}{H}\right)^{\frac{1}{4}}\right)^6 + \left(1.33\left(|\Delta T|\right)^{\frac{1}{3}}\right)^6\right]^{\frac{1}{6}} \qquad (2)$$

$$h_{cn} = 1.57|\Delta T|^{0.31} \qquad (3)$$

Fig 1 graphically illustrates the comparative study done by Wallenten of the various mathematical models developed. Beausoleil-Morrison has highlighted that choosing the right model for h_c can influence the energy consumption predictions by 20-40%.

1.1.2) Forced Convection:- Unlike natural convection, in a forced convection external means are used to push (force) the fluid over the surface. The Nusselt' s number for forced convection is a function of the Reynolds number as shown in equation 4

$$N_{uf} \sim \mathrm{Re}^n \ f(\mathrm{Pr}) \qquad (4)$$

This means that the rate of heat transfer is greatly influenced by the velocity of the air in the room. 1.1.3) Mixed convection:-In most of the real life problems the air flow in an enclosed space like a living room or an office is caused by combination of both natural and forced convection. This type of flow condition is called mixed flow. The complexity of combining the two convective coefficients is mainly due to non-linearity for a given condition. The two can assist or oppose each other depending on the geometry and thermal variation in a room. In 2001 Churchill and Usagi developed a general equation (5) by combining the coefficients of the two into an empirical constant. This is illustrated in fig 2. The summary of the study is given by equation (6).

$$Y = \left(X^a + Z^a\right)^{\frac{1}{a}} \qquad (5)$$

$$h_c = h_{c,Fisher} \frac{\left(T_{surf}\right) - T_{diffuser}}{\left(T_{surf}\right) - T_{roomair}} \qquad (6)$$

Nevertheless, for low air velocity where U→0 it is assumed that overall convective heat transfer $h_c \sim h_{cn}$ likewise for high velocity $h_c \sim h_{cf}$

1.2 Air flow Model

The physics of air flow can be expressed using Continuity, mass, momentum and energy conservation equations; expressed in equation (7).

$$\frac{\partial}{\partial t}(\rho\phi_i) + div(\rho V\phi_i - \Gamma_{\phi_i}\, grad\phi_i) = S_{\phi_i} + S_{buoyancy} \qquad (7)$$

2 AIR FLOW- EXPERIMENTAL STUDY

Standards and official documents (BS EN442-2) layout experimental procedures for testing and evaluating the performance of domestic heating systems, but they do not detail effect of the systems on thermal comfort air flow and quality. The literature covers a wide range of test conditions, some performed in the main area of interest or investigation (ice rinks or train station), while a few were done in scaled models and the others were done in purpose built rooms to focus on a specific aspect of air flow.

The above studies suggest that the main parameters to be measured are temperature and velocity. Common practice is to record the temperature and velocity at the heat source, adjacent surfaces, air at the inlet and exit points for a ventilated system, and near the occupant zone. The secondary measurements involved room surface temperatures, both inside and the outside.

Generic approach to measure temperature was by use of single thermocouples fixed at point of interest. This approach gave a very good representation for a point source, but was limited by the number and location of the thermocouples. To capture temperature variation in the occupant zone (between 0.1m and 1.8 m in the vertical axis) Lariani et al and Qiong et al used poles with thermocouples fixed along the length of the pole. The poles are fixed in the zone of interest and help create a 3-Dimensional temperature matrix. Qiong et al also used infrared thermography to capture any heat lost from heat sources due to radiation. Posner et al used LDA (Laser Doppler Anemometry) and PIV (Particle Image Velocitimetry) to quantify the flow field information and also used smoke machines to help visualize the flow in the room and compare against the PIV images.

The data logging process varied from being fully automated to complete manual recording, cost being the main driving factor. At lower velocities the measurement lacked accuracy due to limitations of the anemometry device. It has also been observed that it very difficult to measure the air velocity near the surfaces and limiting the ability to capture the effect boundary layer. The data from the experiments helps establish boundary conditions for the computational work. CFD (Computation Fluid Dynamics) is the most cost effective solutions to overcome most of the problem encountered in experimentation.

3 MODELING- COMPUTATIONAL FLUID DYNAMICS

CFD (Computational Fluid Dynamics) has been used since 1960's to study, visualize and predict fluid flow for internal and external flows. In early years due to insufficient computational power work was done with 2-Dimensional models which were good for simple models but failed to capture complex 3-dimensional turbulent flow. CFD is a good tool capture data both qualitative and quantitative for any system as long it is supported by good boundary condition for the model, has a suitable solver and has enough computational resource.

The literatures suggest that the best practice is to understand the geometry of the system and obtain the values form an established experimental work. Modeling the wall functions and accounting for radiation heat exchange in the problem increase the accuracy of the flow prediction.

Researchers in the field of air flow have used many different models for their simulation work. The most commonly used models were

a) Laminar flow models
b) LRN (Low Reynolds Number)
c) K-epsilon model
d) K-epsilon model with wall function

Chen in his work has compared Reynolds- stress models with the K-e model. The work shows that K-epsilon model is in agreement with the experimental data for mean velocities along with the Reynolds stress models as shown in fig 3. Nevertheless the K-epsilon model fails to predict the anisotropic and secondary recirculation. Likewise, Posner compared laminar, RNG K-epsilon and standard K-epsilon models with the experimental data and concluded that K-epsilon represented the overall trend but predicted lower velocities fig 4. Contrary to this, Qiong et al found that K-epsilon had the best results for their study of train station building. Weather and Spitler have concluded that (as cited in Lariani et al) that the low-Reynolds K-epsilon was most accurate but required high computing resource.

4 CLOSING REMARKS

The paper has tried to summarize research published in field of air flow prediction in a room using experimental, numerical and analytical methods. This by no means is an exhaustive study and has not covered the entire literature. The study so far reveals that traditionally a convector heater is located under a cold window. The air flow in such a room is caused by the thermal imbalance resulting in buoyant force creating an upward movement of air over the hot surface. The cold air adjacent to the window surface has higher density and has a tendency to move down. This results in the hot air separating from the wall surface approaching the ceiling away from the wall. The wall, ceiling and floor surface temperature greatly influence the air flow and temperature stratification along the vertical axis. Further the flow could be complicated by addition of heat sources (like computers, lights), partitions and occupants. Occupant comfort is quantified primarily on the temperature change experienced by the individual (should not increase 3K) and air velocity in the room. The secondary parameters are air change rate and air contamination. Equation for heat transfer coefficients and air flow have further developed over the years to quantify most of the parameters. The accuracy of the models have been tested for many individual cases against respective experimental work. The scope of research so far was mainly focused to establish accurate predicting tools for conventional heating/cooling systems. Again due to high number of variable and complexity it can be said that each problem has to be evaluated on its own merit. Standalone radiators give flexibility of installation and local temperature variation in a building. Author believes that this aspect has not been evaluated and can possibly help achieve heating at lower operating temperatures.

REFERENCES

FAN ,Y. (1995) *CFD modeling of the air and contaminant distribution in rooms* Energy and Building Vol 23 pp 33-39

GAN G. (1995) *Evaluation of room air distribution systems using computational fluid dynamics* Energy and Building Vol 23 pp 83-93

IMBABI MS AND MUSSET A (1996) *Performance evaluation of a new hybrid solar heating and ventilation system optimized for UK weather conditions* Building and Environment Vol 31 No 2 pp 145- 153

CHEN Q. (1996) *Prediction of room air motion by Reynolds-stress models* Building and Environment Vol 31 No 3 pp 233- 244

WEIZHEN L, HOWARTH AT and JEARY AP (1997) *Prediction of Airflow and Temperature Field in a room with Convective heat source* Building and Environment Vol 32 No 6 pp 541- 550
HUO Y, HAGHIGHAT F, ZHANG JS, and SHAW CY (2000) *A systematic approach to describe the air terminal device in CFD simulation for room air distribution analysis* Building and Environment pp 563- 576
AWBI HB and HATTON A (2000) *Mixed convection from heated room surfaces* Energy and Building Vol 32 pp 152-166
BEAUSOLEIL- MORRISON I (2001) *An algorithm for calculating convection coefficients for internal building surfaces for the case of mixed flow in rooms* Energy and Building Vol 33 pp 351-361
WALLENTEN P (2001) *Convective heat transfer coefficients in a full-scale room with and without furniture* Building and Environment vol 36 pp 743-751
REES SJ, McGRUIK JJ and HAVES P (2001) *Numerical investigation of transient buoyant flow in a room with a displacement ventilation and chilled ceiling system* International journal of heat and mass transfer vol 44 pp 3067-3080
PARK HEE_JIN and HOLLAND D (2001) *The effect of location of a convective heat source on displacement ventilation CFD study* Building and Environment vol 36 pp 883-889
AMPOFO F and KARAYIANNIS TG (2003) *Experimental benchmark data for turbulent natural convection in an air filled square cavity* International journal of heat and mass transfer vol 46 pp 3551-3572
POSNER JD, BUCHANAN CR and DUNN-RANKIN D (2003) *Measurement and prediction of indoor air flow in a model room* Energy and Building vol 35 pp 551-526
BECK SMB, GRINSTED SC, BLAKEY SG and WORDEN K (2004) *Novel Design of Panel Radiators* Applied Thermal Engineering vol 24 1291-1300
SOMARATHNE S SYEMOUR M and KOLOKROTONI M (2005) *Dynamic thermal CFD simulation of a typical office by efficient transient solution method* Building and Environment vol 40 pp 887-896
TASAKA Y and TAKEDA Y (2005) *Effects of heat source distribution on natural convection induced by internal heating* International journal of heat and mass transfer vol 48 pp 1164-1174
BELLACHE O, OZZANE M and GALANIS N (2005) *Numerical prediction of ventilation patterns and thermal processes in ice rink* Building and Environment vol 40 pp 417-426
ZHANG Z and CHEN Q (2006) *Experimental measurements and numerical simulations of particle transport and distribution in ventilated rooms* Atmospheric Environment vol 40 pp 3396-3408
ZHANG Z and CHEN Q (2007) *Comparison of the Eulerian and Lagrangian methods for predicting particle transport in enclosed spaces* Atmospheric Environment vol 41 pp 5236-5248
KONG Q and Yu B (2008) *Numerical study on temperature stratification in a room with under floor air distribution system* Energy and Building vol 40 pp 495-502
LIU W , LIAN Z and YAO Y (2008) *Optimization on indoor air diffusion of floor standing type room air-conditioners* Energy and Building vol 40 pp 59-70
LI Q, et al, (2009) *CFD study of the thermal environment in an air-conditioned train station building* Building and Environment vol 44 pp 1452-1465
CATALINA T, VIRGONE J and KUZNIK F (2009) *Evaluation of thermal comfort using combined CFD and experimentation study in a test room equipped with a cooling ceiling* Building and Environment vol 44 pp 1740-1750
CORGNATI SP, PERINO M, FRACASTORO GV and NEILSEN PV (2009) *Experimental and numerical analysis of air and radiant cooling systems in offices* Building and Environment vol 44 pp 801-806
LARIANI A, NESREDDINE H and GALANIS N (2009) *Numerical and Experimental Study of 3D Turbulent Airflow in a Full Scale heated Ventilated Room* Engineering application of Computational Fluid Mechanics vol 3 No 1 pp 1-14

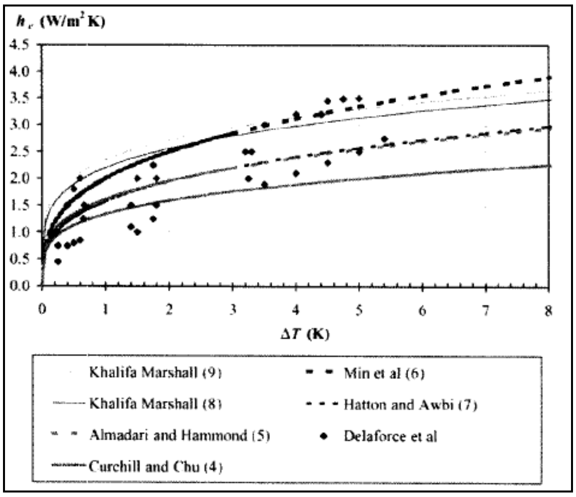

Figure 1: Selection of convective heat transfer coefficient (cited in Wallenten)

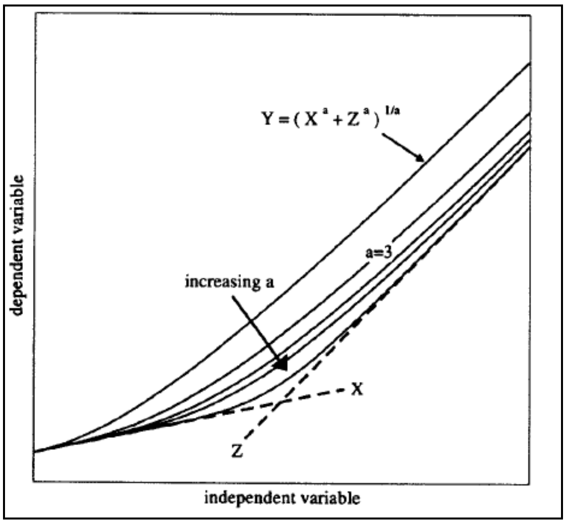

Figure 2: Churchill-Usagi blending approach (cited in Beausoleil)

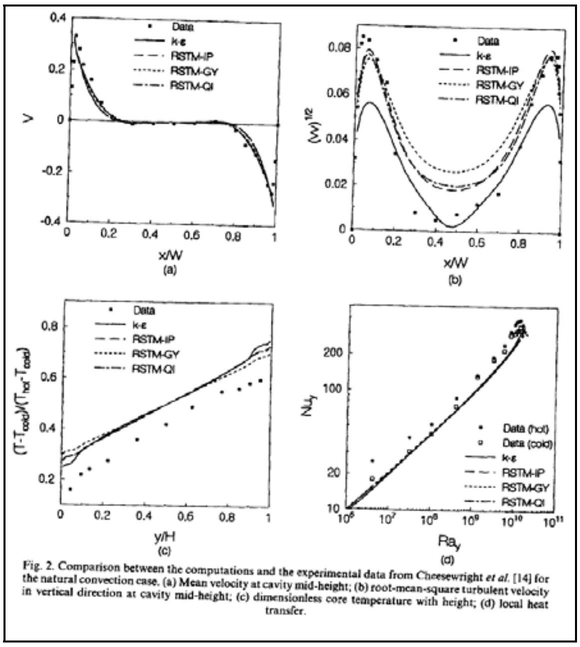

Figure 3: Comparison of Reynolds Stress models and K-e models with the experimental data (cited Chen)

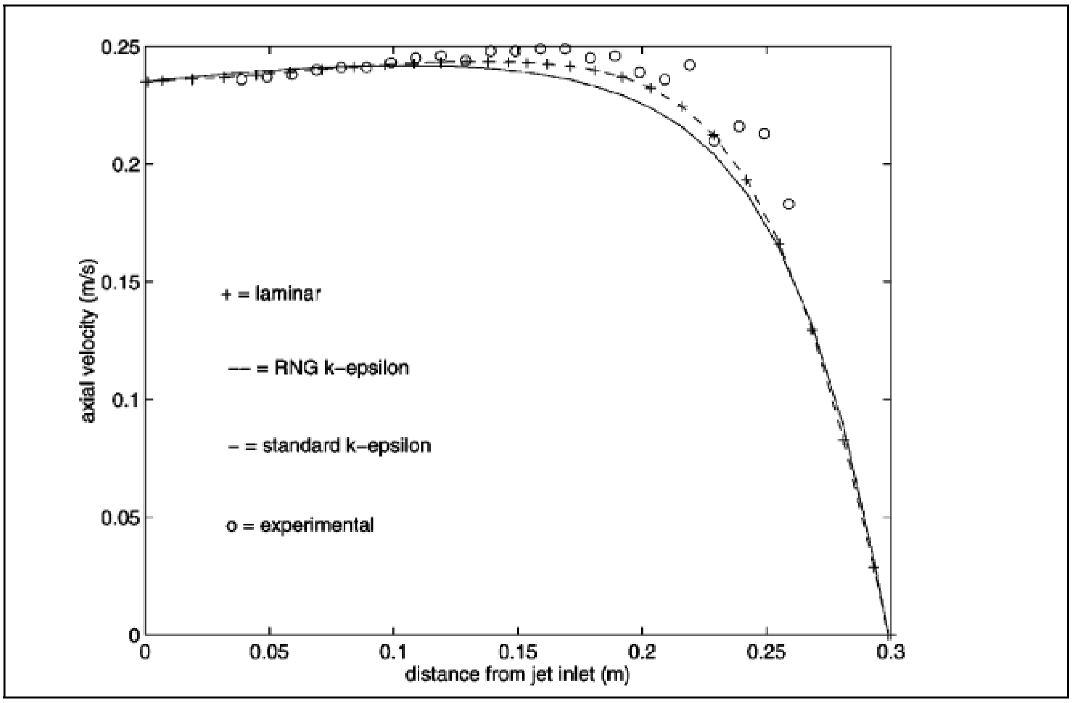

Figure 4: Comparison of LDA measurements and numerical models (cited in Posner)

Symbol	Description
$Q_{convective}$	Heat transfer due to convection
h_c	Total convective heat transfer
h_{cn}	Natural convective heat transfer
h_{cf}	Forced convective heat transfer
$h_{c,Fisher}$	Convective heat transfer from Fisher's equation
A	Surface area
(T_S)	Surface temperature (radiator)
$T_a, T_{roomair}$	Air temperature (room)
T_{surf}	Surface temperature (wall)
$T_{diffuser}$	Air temperature (forced air from ventilation)
ΔT	Temperature difference

Table 1: List of terms