A Plant Component Taxonomy for ESP-r Simulation Environment

T.T. Chow
City Polytechnic of Hong Kong

The layout of air-conditioning systems in building varies dramatically owing to the differences in conceptual design and the relationship between building and plant topologies. Nevertheless all air-conditioning systems have the same basic components which are responsible for the underlying thermofluids and psychrometric functions. Based on a first principles approach, the mass and energy flow in various air-handling equipment has been investigated. 20 primitive parts have been identified which can be put into the ESP-r system to simulate real air han Wing systems. This paper describes the approach and the possibility of extending the coverage to other HVAC systems.

Introduction

Air conditioning systems are often required to operate satisfactorily in a wide range of environmental conditions. This makes the understanding of dynamic plant behaviour relatively important, both at the initial design and later on the system retrofit stages. Plant simulation has been proved a very economical and useful tool in evaluating the dynamic behaviour of equipment and systems. In real buildings the layout of air-conditioning systems varies dramatically owing to the difference in conceptual design and the relationship between building and plant topologies. Accurate modelling of the air conditioning system is important, particularly when the simulation serves the purpose of comparing performance of alternative equipment designs.

Figure 1 shows the basic energy and mass flow paths in relation to some common air-handling systems. It can be seen that all systems have the same basic components - for example, heating and cooling coils, flow convergers and divergers, flow conduits and restrictors, humidifiers and air washers - which are responsible for the underlying thermofluid and psychrometric functions. In this sense, the performance of any air-conditioning system, including the transient responses and the energy consumptions, can be analysed accurately by identifying the exact energy and mass flow paths within or between the components, or amongst the working fluids, the interacting system components and also the immediate surroundings.

In the traditional plant modelling approach, it is usual to reduce the complexity of the real system in order to lessen the computational overhead and the input demands on the user, for instance some energy flow paths may be neglected, time invariant values may be assigned, simplifying boundary conditions may be imposed, or all derivatives may be eliminated to produce a steady-state system. In a new plant simulation approach, none of these assumptions is made. Instead a mathematical model is constructed, subject only to state-of-the-art restrictions, to represent the interactions observed in reality. [Clark 1989]

ESP-r System

Within the ESP-r system all heat and mass flow-paths and their interactions are assigned a counterpart mathematical equivlaent in an attempt to emulate the reality. The entire energy system is then contained within a single numerical framework. At program run time, a building and its plant are made discrete by subdivision into a

---

Division of Technology, City Polytechnic of Hong Kong, Kowloon Tong, Hong Kong.
Phone. (852)7887622 Fax. (852)7888456

number of inter-connecting, finite volumes. These volumes then possess uniform properties which can vary in the time dimension. The ESP-r system therefore provides an excellent platform for simulating the building, the plant, and their interaction through the fundamental modelling approach. [ESRU 1991]

The simultaneous modelling technique actually involves representation of building and/or plant parts (a part of a component, a component, a sub-system, etc.) by discrete nodal schemes.[Clark 1985] To perform the simulation, the user has to specify the building and plant system network corresponds to (part of) a mass flow network - in that the fluid mass flow rates at different parts of the system are computed through the determination of fluid pressure and flow resistances at various flow paths. User mapping of plant system and mass flow network is based on plant component inter-connections versus mass flow network connections. [Hensen 1991] Alternatively user defined mass flow rates can be assigned and based on this the energy flow matrices are solved in each time step. In other cases, the flow rates in some critical parts of the system will be solved by the mass flow network solver and the other parts will have user-assigned flow rates.

Primitive Parts - the Generalisation

In this on-going study, the mass and energy flow in various air-handling equipment has been investigated following a first principles approach. Matrix equations have been derived based on control volume conservation principles, which adheres to the "modular-simultaneous" approach employed by ESP-r. The underlying similarity in the matrix equation structures suggested that air-handling plants in general can be built up from combinations of 20 primitive parts listed in Table 1.

Part numbers 1 to 3 in the table represent the 3 basic modes of heat transfer on and within any solid surfaces. Part numbers 4 to 9 describe the thermal behaviour of moist air flowing in ducts or in free air space. Part numbers 10 to 13 represent the behaviour of water, dry steam, liquid- or superheated-refrigerants in pipes or in accumulating tanks. Part number 14 describes the water spray operations in humidifiers or air washers. Part numbers 15 to 17 refer to the two-phase flow of refrigerant or wet steam in chambers, pipes or tubings. Part number 18 is for steam injection usually taking place in humidifiers. Part numbers 19 and 20 describe the thermal effects of electric heaters when submerged in flowing fluids and in boiling-liquid baths respectively.

Table 1 List of Primitive Parts

Part No.	Description
1	Thermal conduction
2	Surface convection
3	Surface radiation
4	Flow (moist air) upon surface
5	Flow (moist air) upon water spray
6	Flow (moist air) diverger
7	Flow (moist air) converger
8	Flow (moist air) leakage in-to-out
9	Flow (moist air) leakage out-to-in
10	Flow (single-phase fluid) upon surface
11	Flow (single-phase fluid) diverger
12	Flow (single-phase fluid) converger
13	Flow (single-phase fluid) accumulator
14	Water injector
15	Flow (2-phase fluid) upon surface
16	Flow (2-phase fluid) diverger
17	Flow (2-phase fluid) converger
18	Steam injector
19	Heater (moving fluid)
20	Heater (vapour generating)

For illustration purpose, Figure 2 shows the energy and mass flow matrices representation of the primitive part number 4 'flow (moist air) upon surface'. This part describes the thermal interaction between the solid surface, at thermal state S, and the incoming moist air at thermal state A1 and resulted in leaving state A2. Derived from the enthalpy potential theory [ASHRAE 1989], the energy flow matrix determines the temperature conditions of A1, A2 and S at the future time step by the temperature conditions at the present time step and the temperature changes within the time increment due to surface convection and/or moisture condensation if any. Depending on the value of α, the state-equations will be identical to the fully implicit formulation ($\alpha=1$), the fully explicit formulation ($\alpha=0$), or for instance the Crank-Nicolson formulation ($\alpha=0.5$) [Chapra and Canale 1988]. The mass flow matrices simply relate the mass flow rates of dry air and water vapour (moisture) respectively at the incoming stream to the leaving stream. This primitive part can well define the thermal behaviour of moist air flowing inside an air duct, or outside a heating or cooling coil surface. In the real world there is no difference in energy nor mass flows comparing moist air flowing in a duct with moist air flowing over a cooling coil; in either case when the temperature of the solid surface drops below the dew point, condensation will occur.

The plant system is a combination of component models forming a complete set of state-equations for the whole system. At run time, each component has corresponding subroutine whose mission is to generate the coefficients (say a_{ij}, b_{ij} and c_{ij} in Figure 2 where $i, j = 1, 2$ or 3) of these equations. A number of generic subroutines are also necessary which perform tasks such as computing temperature dependent specific heat, density, viscosity, or heat of vaporization for the working fluids of interest, i.e. dry air, water vapour, water or refrigerant. Computation of the flow dependent heat transfer coefficients and mass diffusion coefficients are also essential.

Concept of Plant Component Taxonomy

In the ESP-r simulation environment, each of these primitive parts can be represented by a 'primitive part' subroutine in the plant component database. In order to simulate the performance of one air conditioning system component, like a particular chilled water cooling coil, a 'single component' subroutine for this coil can be built from the primitive part subroutines. For instance, in the first step, a straight tube section of the coil can be modelled by a combination of the part numbers 4, 1 and 10 each representing the external surface, tube metal, and the internal surface respectively. Each tube is therefore a '4 node' model. Then the single component 'cooling coil' can be built up by a network of the tube sections connected in the same configuration as in the actual physical arrangements, i.e. single pass, serpentine or double serpentine arrangements. In this way a chilled water coil of 4 rows and 16 columns in double serpentine arrangement will be represented by more than 300 nodes. More complicated or simplified models can be built upto the developer's discretion.

Other single component subroutines i.e. hot water coils, DX coils, air dampers, motor-driven fans, humidifiers, electric heaters etc. can be built in the similar manner, making use of the appropriate primitive parts. Each 'single component' subroutine will be accompanied by additional subroutines for data input management and for checking the validity of designer specified parameters prior to the actual simulation. To model a commercial product like an AHU, a 'meta component' subroutine can be generated based on a selection of the above mentioned single component subroutines. In this way, theoretically the performance of any commercial product can be analysed. The sensitivity of alternative equipment design - even the effect of slight changes in equipment configuration or dimensions - can be tested through computer simulation, all depending on the degree of complexity of the nodal scheme.

Such a class taxonomy concept applying in plant simulation provides an opportunity for the simulationists to have greater flexibility in creating new component models in the plant database and spend less effort on writing and compiling source code. The concept can also be modified to apply in an object-oriented programming environment where emphasis has placed on encapsulation, inheritance and hierarchy. [Cox 1987] The possibility of use in the Energy Kernel Systems [Sowell 1991] has to be investigated.

One of the principal barriers to the use of this explicitly modelling approach is the problem of data preparation in the face of uncertainty. Plant models require a substantial amount of input data and obviously much of this is difficult to obtain. This is not necessarily a justification for a simplification of the laws of thermodynamics so that a model can be developed which operates with a reduced data set. An alternative possibility is to retain the best representation of reality - a high integrity simulation model - and, instead, to generate the complete data set from whatever information the designer can offer at any stage. [Clark 1989] For instance in lack of accurate information the designer might select any empirical expressions of the heat transfer or mass diffusion coefficients at hand and replace them later on by more relevant substituents once available. In all cases, accuracy of the model has to be verified by program validation. This approach lays emphasis on state-of-the-art intelligent design tools as opposed to simplified design tools.

Future development

With advances in machine technology, the performance/cost ratio of these systems will rise rapidly and the technology will become more widely applied. Subject to program validation, component modelling making use of the 20 primitive parts mentioned above can be used to simulate real air handling systems. It is envisaged that the same can be used to model hydronic or refrigeration circuits. With the selective addition of some extra primitive parts, for instance those describing combustion heat transfer, ice formation, chemical adsorptions etc., the plant database can be extended to simulate different HVAC&R plants or any other thermal systems.

References

ASHRAE. 1989. Handbook: Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

Chapra S.C.; and Canale R.P. 1989. Numerical Methods for Engineers. 2nd ed. McGraw-Hill.

Clark, J.A. 1985. Energy Simulation in Building Design. Adam Hilger.

Clark, J.A. 1989. "Building Energy Simulation: the State-of-the-Art." Solar & Wind Technology Vol.6, no. 4: 345-355.

Cox, B.J. 1987. Object Oriented Programming: An Evolutionary Approach. Addison Wesley.

ESRU. 1991. "ESP-r: a Building and Plant Energy Simulation System Version 7 Series". Energy Simulation Research Unit Manual U91/1, University of Strathclyde, Scotland.

Hensen J.L.M. 1991. "On the Thermal Interaction of Building Structure and Heating and Ventilation System." PhD Thesis, FAGO Units, Eindhoven University of Technology, The Netherlands.

Sowell E.F. 1991 "Next Generation Building Services Engineering Software Opportunities for the Practitioner". In Proceedings of BEP'91 Conference (Canterbury, U.K., Apr. 10-11) pp 1-9.

Nomenclature (for Figure 2)

A = area
C = specific heat capacity of solid
Cp = specific heat of fluid at constant pressure
g = moisture content
h = heat transfer coefficient
Kd = mass diffusion coefficient
M = mass
m = mass flow rate
θ = temperature
t = time

Subscripts

a = air
fg = latent
s = surface
v = water vapour

Superscripts

* = present time step

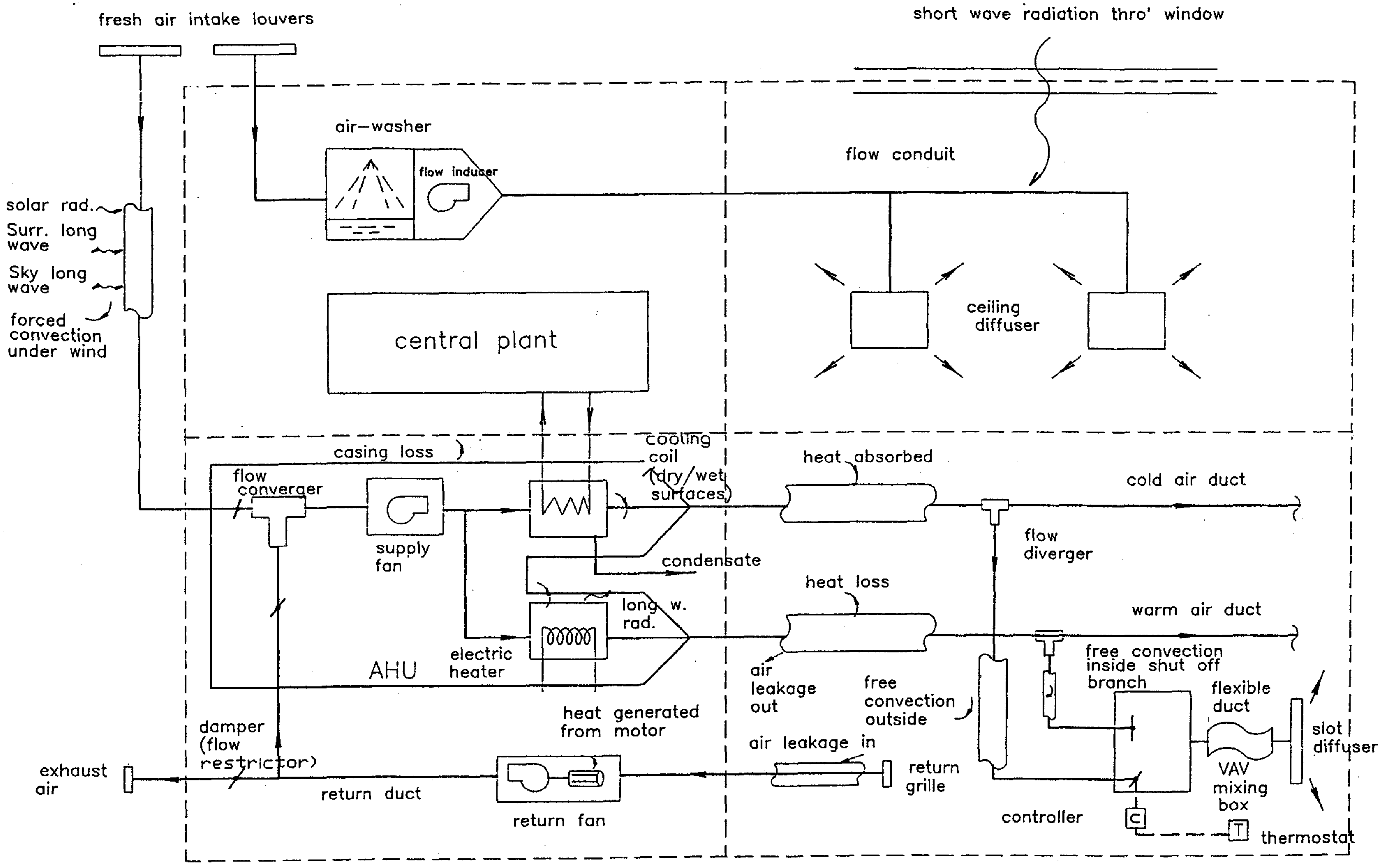

Figure 1 Basic energy & mass flow paths in air-handling systems

P21 Flow (moist air) upon surface


(a) external flow

(b) internal flow

Energy flow matrix :

$$\begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{vmatrix} \times \begin{vmatrix} \theta_{a1} \\ \theta_{a2} \\ \theta_{s} \end{vmatrix} = \begin{vmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \end{vmatrix} \times \begin{vmatrix} \overset{*}{\theta}_{a1} \\ \overset{*}{\theta}_{a2} \\ \overset{*}{\theta}_{s} \end{vmatrix} + \begin{vmatrix} c_{11} \\ 0 \end{vmatrix}$$

where
$a_{11} = \alpha\ (C_{a1} - C_{as})$
$a_{12} = -\ \alpha\ (C_{a2} + C_{as}) - (M_aC_{pa}/\delta t)$
$a_{13} = 2\alpha\ C_{as}$
$a_{21} = \alpha\ C_{as}$
$a_{22} = \alpha\ C_{as}$
$a_{23} = -\ 2\alpha\ C_{as} - (M_s\ C_s/\delta t)$

$b_{11} = -\ (1 - \alpha)\ (C_{a1} - C_{as})$
$b_{12} = (1 - \alpha)\ (C_{a2} + C_{as}) - (M_aC_{pa}/\delta t)$
$b_{13} = -\ 2(1 - \alpha)\ C_{as}$
$b_{21} = -(1 - \alpha)\ C_{as}$
$b_{22} = -(1 - \alpha)\ C_{as}$
$b_{23} = 2(1 - \alpha)\ C_{as} - (M_s\ C_s/\delta t)$

$c_{11} = \alpha\ C_{av} + (1 - \alpha)\ \overset{*}{C}_{av}$
$c_{21} = 0$

Notes :

1. $C_{a1} = m_{a1}\ C_{pa} + m_{v1}\ C_{pv}$
$C_{a2} = m_{a2}\ C_{pa} + m_{v2}\ C_{pv}$
$C_{as} = 0.5\ h_{as}\ A_{as}$
$C_{av} = -\ h_{fg}\ (m_{v1} - m_{v2})$

2. For dry surface, $m_{v1} = m_{v2}$
so $C_{av} = 0$

Mass flow matrix :
for dry air,

$$\begin{vmatrix} 1 & -1 \end{vmatrix} \times \begin{vmatrix} m_{a1} \\ m_{a2} \end{vmatrix} = \begin{vmatrix} 0 \end{vmatrix}$$

for water vapour,

$$\begin{vmatrix} 1 & -1 \end{vmatrix} \times \begin{vmatrix} m_{v1} \\ m_{v2} \end{vmatrix} = \begin{vmatrix} C_{12} \end{vmatrix}$$

where $C_{21} = K_d\ A_{as}\ (\bar{g}_a - g_s)$ and for dry surface, $C_{21} = 0$

Figure 2 Matrix representation of Primitive Part No. 4