Generalization in Plant Component Modelling

T.T. Chow
Division of Technology
City University of Hong Kong

ABSTRACT

In computer simulation, accurate modelling of air conditioning equipment is important in the studies of dynamic plant performance, for instance in the selection process of a plant control scheme, in the investigation of plant energy consumptions, or in the detailed design of a plant equipment. With the advancements in computer speed and manmachine: interface, a new generalized plant simulation approach can be used which represents the energy and mass flow paths by the primitive parts as the basic elements in constructing plant components. This paper explains the mathematical concepts and presents some illustrative examples with simulation results validated by analytical solution and inter-model comparisons. Advantages and possible future developments are also addressed.

INTRODUCTION

A number of new developments are taking place in different countries to seek for a better simulation environment for the next generation building-and-plant appraisal softwares. There is a trend moving towards a highly modular object-based component modelling approach. (Sowell 1991; Wright et al 1992) A first and obvious way to make the modelling task more efficient is the re-use of existing component or sub-component models as far as possible. This means that the modelling process is firstly to segregate the physical component into pieces, then to select the appropriate basic models from the plant library to represent each piece, and finally to link these basic models to produce the desired compound or meta model (Laret 1989; Dubios & Antipolis 1990). One most generalized way of achieving this is however through the use of a library of atomic objects known as the primitive parts (Chow 1993) which adopt the finite difference approach as in the ESP-r system (Clarke 1985; Aasem et al 1993).

PRIMITIVE PARTS

Each primitive part is a small finite difference control volume conservation-equation-set that describes one particular aspect of thermofluid process through a minimum number of nodes. Air conditioning equipment can be modelled from some combinations of the primitive parts, of which a list is shown in Table 1. Included in the list are 27 objects placed under 10 categories. Categories 1 to 3 describe the 3 basic modes of heat transfer. Here different primitive parts are used to describe different situations, say whether the thermal state of the ambient air, or a neighboring surface, or a solid node in direct contact, is: (i) a state variable to be solved in the solution process, or (ii) a known value (external excitation) throughout the entire simulation period. Category 4 describes the thermal behaviour of fluid flowing across a solid surface. Fluid types here include moist air and any pure fluid - be it a liquid or gas (single-phase), or a wet vapour (two-phase). There is no restriction on the physical shape, orientation, nature, or dimensions of the surface - be it the interior surface of a fan casing or the exposed surface of a duct heater. While a 3-node primitive part for a single-phase fluid or moist air stream flowing upon surface is required to describe the transport delay phenomenon, a 2-node representation is usually adequate for general applications. Three nodes for 2-phase flow are required since the leaving fluid can be superheated or subcooled and therefore its temperature may deviate from the saturated value. Categories 5 and 6 describe the occurrences of splitting, mixing or induction of fluid streams. The primitive parts here are basic objects for modelling tees, mixing box, and fan. The flow multiplier is helpful to allow an adjustment to the fluid flow rate in order to simplify a modelling task by narrowing down the modelling scope of the real piece; it can also act as a "filter", say in the case of a steam trap which allows liquid water to pass through but not steam vapour. Fluid mass flow rate of a flow inducer can be user specified or determined at each time step by the ESP-r fluid flow network solver (Hensen & Clarke 1991) incorporating the fan/pump curve with the instantaneous flow resistances of other system components. Category 7 describes the direct interaction of air and water streams, as it is in the case of air washer or cooling tower. Category 8 describes the injection of water or steam into a moist air stream

- a process typically found in humidifiers. Category 9 covers the fluid accumulators like the expansion tank of a hydronic circuit, or the room space when it is treated as a plant-like component. Category 10 covers the heat injection processes, like the operation of an electric heating element in an air duct or a water bath, etc.

In a modular simultaneous simulation environment, each of these primitive parts can exist as an individual subprogram. Other plant component or sub-component subprograms, once have the nodal schemes fixed during the modelling process, can be written to call upon the primitive part subprograms and in addition, the other subprograms for data input management, for computing time-varying properties and empirical coefficients and where necessary, for checking the validity of user specified parameters prior to the start of the simulation run. Similarly a meta component can be built upon a combination of these single plant components or sub-components. In this way the entire plant database will be built upon a finite number of primitive parts as the core and therefore with a unified mathematical structure and hierarchy. The basic method is illustrated below.

COMPONENT MODELS

An insulated water pipe component model with 4 nodes is shown in Figure 1(a). Two solid nodes S1 and S2 are used to represent the thermal insulation and the metallic pipe body respectively. Two other nodes are in the water stream. The water in contact node WM represents the entire water volume inside the pipe and its state variables describe the average water condition in the pipe. The leaving water node W1 actually occupies no physical space and does not represent any fluid mass in the water stream. Its existence serves to pass leaving water information (e.g. transport delay) to the downstream component. W0 is a connecting node belonging to an upstream component. The temperature of the ambient air (node E) is taken as an external excitation to the thermal exchange at the pipe external surface. The energy balance equations for the four nodes are therefore

for thermal insulation,

$$h_o A_o(\theta_e - \theta_{s1} + k_{12}A_{12}(\theta_{s2} \quad \theta_{s1}) = M_{s1}C_{s1}\frac{d\theta_{s1}}{dt} \qquad (1)$$

for metallic pipe,

$$k_{12}A_{12}(\theta_{s1} - \theta_{s2}) + h_i A_i(\theta_{wm} \quad \theta_{s2}) = M_{s2}C_{s2}\frac{d\theta_{s2}}{dt} \qquad (2)$$

for water in contact,

$$m_{w0}Cp_{w0}\theta_{w0} - m_{w1}Cp_{w1}\theta_{w1} + h_i A_i(\theta_{s2} \quad \theta_{wm}) = M_{wm}Cp_{wm}\frac{d\theta_{wm}}{dt} \qquad \ldots(3)$$

and for leaving water (in the case of no transport delay)

$$\theta_{w1} = \theta_{wm} \qquad (4)$$

By a weighed mix of the fully-implicit and fully-explicit finite difference schemes (Hensen 1991), it can be shown that the matrix template of this component (for both energy and mass flows) is in the form of

$$\begin{bmatrix} C(1) & C(2) & 0 & 0 & 0 \\ C(3) & C(4) & C(5) & 0 & 0 \\ 0 & C(6) & C(7) & C(8) & C(11) \\ 0 & 0 & C(9) & C(10) & 0 \end{bmatrix} * \begin{bmatrix} S1 \\ S2 \\ WM \\ W1 \\ W0 \end{bmatrix} \quad \begin{bmatrix} C(12) \\ C(13) \\ C(14) \\ C(15) \end{bmatrix} \qquad (5)$$

for the five nodes S1, S2, WM, W1 and W0. At the time of solving fluid mass flow balance some of the above matrix coefficients will have zero values. If the simulation time step is less than the flushing time, the transport delay subprogram will be active and the values of θ_{wm} and θ_{w1} will then be determined by the transport delay subprogram.

This model can be formulated by means of the following 3 primitive parts:

Part No. 1.1	Thermal conduction (solid to solid)
Part No. 2.4	Surface convection (with ambient)
Part No. 4.3	Flow upon surface (for single-phase fluid)

Descriptions of these 3 primitive parts are given in Figures 2, 3 and 4 respectively.

The 15 matrix coefficients in equation (5) can be expressed as the arithmetic sums of the primitive part coefficients as shown in Table 2. The values of Ni - an indicator showing the number of primitive parts in which a particular node has been involved - for S1, S2, WM and W1 are respectively 2, 2, 1 and 1. These values is required to give a correct representation of the conservation equations for each node.

In a similar way a chilled water cooling coil model can be constructed through several stages. In the first place a straight tube section of the coil can be modelled by a combination of the part numbers 4.3 and 4.4. Then the cooling coil can be represented by a network of these tube sections connected in the same configuration as in the actual physical arrangements, for instance Figure 1(b) shows a 4-row counter-flow arrangement. The coil is therefore a 12-node model. More detailed representation of the coil can be constructed upto the modeller's discretion. Empirical formulae of the matrix coefficients in the component models can always be replaced by more accurate correlations in future without any change to the primitive parts library.

MODEL VALIDATION

Very accurate results can be obtained by this approach when the heat and mass transfer data and correlations are readily known. Figure 1(c) shows the comparisons of the dynamic response of leaving water temperature of the above water pipe model (at steady flow rate and with a step change in inlet water temperature from 5 to 10 ^{o}C) with the analytical solution worked out from the Tobias transfer function (1973) and the simulation results from the HVACSIM^{+} software (Clark 1985). It can be seen that the 3 curves are close. Slight oscillations can be observed on the HVACSIM^{+} curve and this is a side-effect of using a fifth-order time-dependent polynomial to model the axial temperature distribution. Figure 1(d) compares the effect of a unit step change in inlet water temperature on the leaving air temperature (normalized) of the coil model under latent cooling. The results again indicate very good matching in the dynamic solutions between the primitive part (PP) model and the HVACSIM^{+} software.

ADVANTAGES

The primitive parts are the basic elements upon which any plant sub-components, equipment or systems can be built. A number of advantages can be identified for this generalised and explicit modelling approach. They are:

i) input-output free and simultaneous modelling environment,
ii) use of fundamental modelling approach,
iii) flexible description of real systems with reasonable accuracy,
iv) thorough information for results analysis,
v) controlled complexity and integrity of source code,
vi) modular and hierarchical object oriented features,
vii) simplified software maintenance, development and validation work,
viii) facilitating joint research efforts.

In an input-output free environment, the same component models can be transferred to work in more than one simulation platform. One simpliest way to achieve this is to develop the generalised plant library in a neutral model format, which can then be added to any simulation environment through the use of translators (Bring et al 1992). The work, when moving in the direction of product modelling, will benefit the integrated intelligent building-design systems in the long run (Augenbroe & Winkelmann 1991).

CONCLUSIONS

Component modelling by primitive parts provides a unified mathematical structure which can retain the complexity of plant components in the real world, the convenience for the modellers to develop new models for various applications, and the potential for the models of to-day to be upgraded in pace with the state-of-the-art technology in the future. Decomposing a plant component into primitive pieces that precisely describe a distinct combined energy and mass flow behaviour allows the representation of all real components by a minimum set of sub-parts in the plant database and yet the maximum flexibility upto the modeller's personal perception of the best way to perform a simulation task. When this plant component taxonomy concept is fully established and implemented, most plant components for system simulation may not exist in the source code at all. Instead, through automatic model construction (Tang & Clarke 1993), each component is user-created by a selective linkage of the sub-parts from a plant component library, with a specific simulation task in the user's mind. The system model is finally defined by specifying the inerconnections between these components. The approach is then close to the highly flexible building-side simulation methods that we are enjoying in these days.

REFERENCES

Aasem E O et al 1993 ESP-r: a program for building energy simulation, Version 8 Series, Energy Simulation Research Unit, ESRU Manual U93/1, University of Strathclyde, Glasgow, U.K.

Augenbroe & Winkelmann 1991 "Integration of simulation into the building design process", in Proceedings of the Building Simulation '91 the 2nd international conference, IBPSA, Nice, France, August, pp.367-374.

Bring et al 1992 The Neutral Model Format for building simulation, final report, Department of Building Services Engineering, Royal Institute of Technology, Stockholm, Sweden.

Chow T T 1993. "A plant component taxonomy for ESP-r simulation environment", in Proceedings of the Building Simulation '93 the 3rd international conference, IBPSA, Adelaide, Australia, August, pp.429-434.

Clark D R 1985 HVACSIM$^+$ building systems and equipment simulation program reference manual, NBSIR 84-2996, Department of Commerce, U.S.

Clarke J A 1985 Energy simulation in building design, Adam Hilger Ltd., Bristol.

Dubois A & Antipolis S 1990 "Component model documentation and management: the evolution of the proforma and modelotheque", in Proceedings of System Simulation in Buildings the 3rd international conference, Liege, Belgium, December, pp.17-39.

Hensen J L M 1991 "On the thermal interaction of building structure and heating and ventilating system", PhD thesis, the FAGO Unit, Eindhoven University of Technology, Netherland.

Hensen J L M & Clarke J A 1991 "A fluid flow network for integrated building and plant energy simulation", in Proceedings of System Simulation in Buildings the 3rd international conference, Liege, Belgium, December, pp.151-167.

Laret L 1989 "Building & HVAC simulation: the need for well-suited models", IBPSA Building Simulation '93, in Proceedings of Building Simulation '89, the ist international IBPSA conference, Vancouver, Canada, June, pp.199-204.

Sowell E F 1991 "Next generation building services engineering software opportunities for the practitioner", in Proceedings of BEP '91 Conference, Canterbury, U.K., April, pp.1-9.

Tang D & Clarke J A 1993 "Application of the object oriented programming paradigm to building plant system modelling", in Proceedings of the Building Simulation '93 the 3rd international conference, IBPSA, Adelaide, Australia, August, pp.317-323.

Tobias J R 1973 "Simplified transfer function for temperature response of fluids flowing through coils, pipes or ducts", ASHRAE Transactions, Vol.79, pp.19-22.

Wright A J, Bloomfield D, & Wilshire T J 1992 "Building simulation and building representation: overview of current developments", Building Services Engineering Research & Technology, No.13, Vol.1, pp.1-11.

NOMENCLATURE

Symbols

A	area
A(i,j)	future time step coefficient
B(i,j)	present time step coefficient
C	specific heat of solid
C(i)	the ith matrix coefficient
Cp	specific heat of fluid at constant pressure
h	heat transfer coefficient
k	thermal conductivity
M	mass
m	mass flow rate
Ni	primitive part connection index
S	solid
t	time
U	overall heat transfer coefficient
W	water
α	weighing factor
θ	temperature

Superscript

	present time step

Subscripts

0-4	node identification numbers
e	ambient
i	internal
m	mean
o	external
s	solid
sat	saturated
w	water

Table 1 List of Primitive Parts

1 **Thermal conduction**
  1.1 solid to solid
  1.2 with ambient solid

2 **Surface convection**
  2.1 with moist air
  2.2 with 2-phase fluid
  2.3 with 1-phase fluid
  2.4 with ambient

3 **Surface radiation**
  3.1 with local surface
  3.2 with ambient surface

4 **Flow upon surface**
  4.1 for moist air; 3 nodes
  4.2 for 2-phase fluid; 3 nodes
  4.3 for 1-phase fluid; 3 nodes
  4.4 for moist air; 2 nodes
  4.5 for 1-phase fluid; 2 nodes

5 **Flow divider & inducer**
  5.1 Flow diverger (for all fluid)
  5.2 Flow multiplier (for all fluid)
  5.3 Flow inducer (for all fluid)

6 **Flow converger**
  6.1 for moist air
  6.2 for 2-phase fluid
  6.3 for 1-phase fluid
  6.4 for leak-in moist air from outside

7 **Flow upon water spray**
  7.1 for moist air

8 **Fluid injection**
  8.1 water/steam to moist air

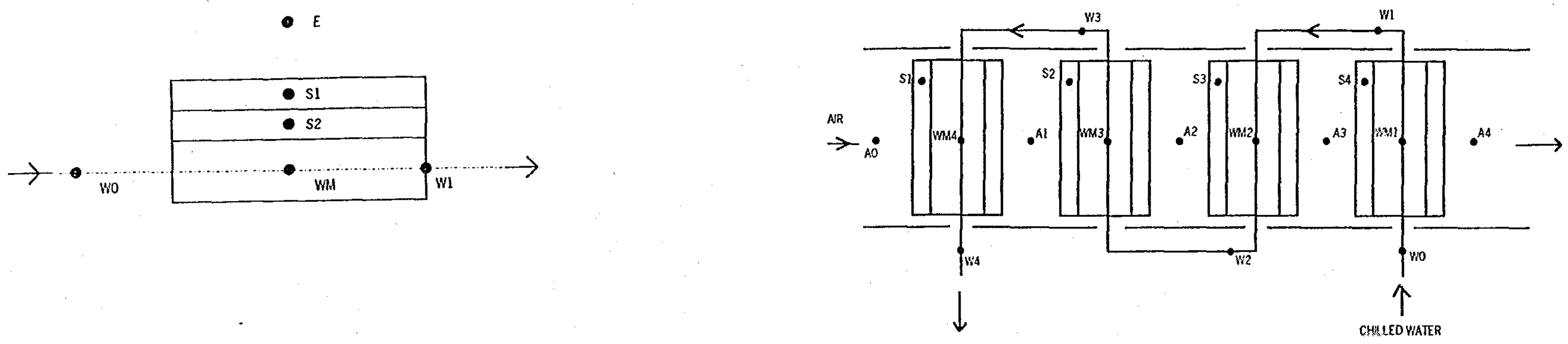
9 **Fluid accumulator**
  9.1 for moist air
  9.2 for liquid

10 **Heat injection**
  10.1 to solid
  10.2 to vapour-generating fluid
  10.3 to moist air

Table 2 Development of Insulated Water Pipe Model from Primitive Part Coefficients

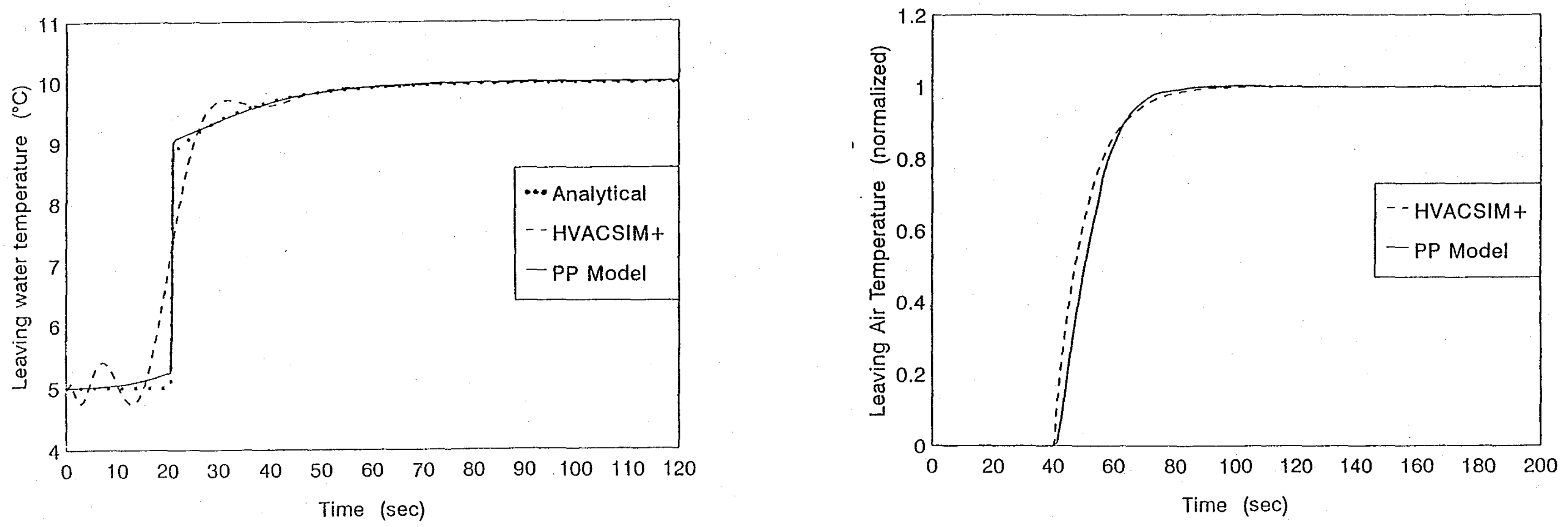
Matrix Coefficients		**PP 1.1** Thermal conduction (solid to solid) S1,S2		**PP 2.4** Surface convection (with ambient) S1,E		**PP 4.3** Flow upon surface (for 1-phase fluid) S2-W1,WM,W0
C(1)	=	A(11,1)	+	A(24,1)		
C(2)	=	A(11,2)				
C(3)	=	A(11,3)				
C(4)	=	A(11,4)			+	A(43,1)
C(5)	=					A(43,2)
C(6)	=					A(43,4)
C(7)	=					A(43,5)
C(8)	=					A(43,6)
C(9)	=					A(43,8)
C(10)	=					A(43,9)
C(11)	=					A(43,11)
C(12)	=	B(11,1)	+	B(24,1)		
C(13)	=	B(11,2)			+	B(43,1)
C(14)	=					B(43,2)
C(15)	=					B(43,3)

Note : A(i,j) represents the future time step coefficients and B(i,j) the present time and excitation coefficients.



(a) An Insulated Pipe Model

(b) A 4-row Counter-flow Cooling Coil Model



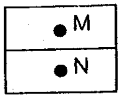
(c) Comparison of Pipe Model Simulation Results

(d) Comparison of Cooling Coil Model Simulation Results

Figure 1 Component Models built upon Primitive Parts and Simulation Results Validation

Part No. 1.1 Thermal Conduction (solid to solid)

2 No. of Nodes :
M - solid
N - solid



Template :

$$\begin{bmatrix} A(11,1) & A(11,2) \\ A(11,3) & A(11,4) \end{bmatrix} * \begin{bmatrix} M \\ N \end{bmatrix} = \begin{bmatrix} B(11,1) \\ B(11,2) \end{bmatrix}$$

Energy flow matrix :

A(11,1) = $- \alpha C_{mn} - M_m C_m/(Ni_m \delta t)$

A(11,2) = αC_{mn}

A(11,3) = αC_{mn}

A(11,4) = $- \alpha C_{mn} - M_n C_n/(Ni_n \delta t)$

B(11,1) = $[(1- \alpha) C_{mn} - M_m C_m/(Ni_m \delta t)]\theta_m{}^* - (1-\alpha) C_{mn} \theta_n{}^*$

B(11,2) = $[(1- \alpha) C_{mn} - M_n C_n/(Ni_n \delta t)]\theta_n{}^* - (1-\alpha) C_{mn} \theta_m{}^*$

where C_{mn} = reciprocal of thermal resistance between M and N

Mass flow matrix (for both first and second phase mass balance):

A(11,1) = $1/Ni_m$

A(11,2) = 0

A(11,3) = 0

A(11,4) = $1/Ni_n$

B(11,1) = 0

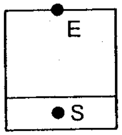
B(11,2) = 0

Figure 2 Primitive Part No. 1.1

Part No. 2.4 Surface Convection (with ambient)

1 No. of Node:
S - solid (or fluid)

1 No. of Boundary Condition:
E - boundary fluid



Template:

$$[A(24,1)]*[S]=[B(24,1)]$$

Energy flow matrix

A(24,1) = $- \alpha C_{es} - M_s.C_s/(Ni_s.\delta t)$

B(24,1) = $[(1- \alpha) C_{es} - M_s C_s/(Ni_s \delta t)]\theta_s{}^* - [\alpha C_{es} \theta_e + (1-\alpha) C_{es} \theta_e{}^*]$

where C_{es} = $h_{es} A_{es}$ for solid
= $U_{es} A_{es}$ for fluid

Mass flow matrice

for first phase(liquid):

A(24,1) = $1/Ni_s$

B(24,1) = 0

for second phase (vapour):

A(24,1) = $1/Ni_s$

B(24,1) = 0

Notes:

1. The thermal state of the boundary fluid in bulk is taken as not affecting by the heat exchange with the surface; θ_e thus becomes an external excitation and its values during the simulation period is user specified.

2. Possibility of mass exchange (e.g. condensation) on the surface is not considered.

Figure 3 Primitive Part No. 2.4

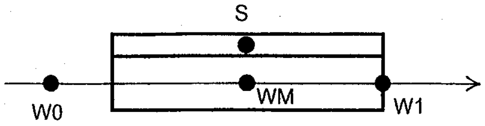
Part No. 4.3 Flow upon surface (for single-phase fluid; 3 nodes)

3 Nos. of Nodes :

S - solid surface
WM - fluid in contact
W1 - leaving fluid

1 No. of Connection :

W0 - incoming fluid



Template :

$$\begin{bmatrix} A(43,1) & A(43,2) & 0 & 0 \\ A(43,4) & A(43,5) & A(43,6) & A(43,11) \\ 0 & A(43,8) & A(43,9) & 0 \end{bmatrix} * \begin{bmatrix} S \\ WM \\ W1 \\ W0 \end{bmatrix} = \begin{bmatrix} B(43,1) \\ B(43,2) \\ B(43,3) \end{bmatrix}$$

Energy flow matrix :

$A(43,1) = -\alpha C_{sw} - (M_s C_s / Ni_s.\delta t)$

$A(43,2) = \alpha C_{sw}$

$A(43,4) = \alpha C_{sw}$

$A(43,5) = -\alpha C_{sw} - M_w Cp_w / Ni_{w1}.\delta t$

$A(43,6) = -\alpha C_{w1}$

$A(43,8) = -1$

$A(43,9) = 1$

$A(43,11) = \alpha C_{w0}$

$B(43,1) = [(1-\alpha) C_{sw}{}^* - M_s C_s/(Ni_s \delta t)]\theta_s{}^* - (1-\alpha) C_{sw}{}^* \theta_{wm}{}^*$

$$B(43,2) = -(1-\alpha) C_{sw}{}^* \theta_s{}^* + [(1-\alpha) C_{sw}{}^* - M_w Cp_{wm}{}^* /(Ni_{wm}\delta t)]\theta_{wm}{}^* - (1-\alpha) C_{w1}{}^* \theta_{w1}{}^* - (1-\alpha) C_{w0}{}^* \theta_{w0}{}^*$$

$B(43,3) = 0$

where, M_w = mass of fluid in the control volume
Cp_{wm} = specific heat of fluid θ_{wm}
C_{w0} = $m_{w0}\, Cp_{w0}$
C_{w1} = $m_{w1}\, Cp_{w1}$
C_{sw} = $h_{sw}\, A_{sw}$

In case the DELAY flag is ON, the following coefficients will be revised as:

$A(43,4) = 0$
$A(43,5) = 1$
$A(43,6) = 0$
$A(43,8) = 0$
$A(43,11) = 0$
$B(43,2) = \mathrm{DELAY}(\theta_{wm})$
$B(43,3) = \mathrm{DELAY}(\theta_{w1})$

Mass flow matrice :

for first phase (liquid state):

$A(43,1) = 1/Ni_s$
$A(43,2) = 0$
$A(43,4) = 0$
$A(43,5) = 1/Ni_{wm}$
$A(43,6) = 0$
$A(43,8) = -1$
$A(43,9) = 1$
$A(43,11) = -1$
$B(43,1) = 0$
$B(43,2) = 0$
$B(43,3) = 0$

for second phase (vapour state):

$A(43,1) = 1/Ni_s$
$A(43,2) = 0$
$A(43,4) = 0$
$A(43,5) = 1/Ni_{wm}$
$A(43,6) = 0$
$A(43,8) = 0$
$A(43,9) = 1$
$A(43,11) = 0$
$B(43,1) = 0$
$B(43,2) = 0$
$B(43,3) = 0$

Figure 4 Primitive Part No. 4.3