ON THE SELECTION OF FLOWGRAPH

ISAMI YOSHIFUKU

Department of Chemical Engineering, Kagoshima University, Kagoshima 890

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In the previous paper, the solution to the packed tower process problem was proposed in the form of sequential cell flowgraph (abbreviated hereafter to FG) representation. There, because of space limitation, the question of how to choose an adequate one among several FGs constructed was not considered.

In this report, a convergence test of FG is proposed and its application to the selection of FG in the cooling tower process problem is described.

1. Convergence Test of Flowgraph

The procedure to construct the n-th cell FG is shown briefly. First, the tower height is divided equally, and the fundamental equations for the n-th cell are enumerated. Second, each of these equations is transformed into a FG unit and these units are connected to form an n-th cell FG. Generally, there are several n-th cell FGs by the combination of FG units, and it becomes a serious problem that we must decide which FG is to be adopted.

As stated earlier, the n-th cell FG consists of left-hand side variables (tearing variables, connection variables and others) column and an arrangement of variables in the right direction. The tearing variable is the variable assumed first and calculated later repeatedly in the trial-and-error method. Next, the calculation should be continued until a convergence inequality is satisfied.

We shall limit our consideration here to the first calculation of the first cell (n = 1) in an n-th cell FG to be tested, which means that trial-and-error calculation is not yet started. The curve plotted in a diagram where abscissa and ordinate are, respectively, the assumed and the calculated value of a tearing variable, provided that other tearing variables remain constant, is denoted as the characteristic curve (Ch curve hereafter) of the tearing variable. Hence, it is noted that the number of Ch curves appearing in a FG is equal to the number of tearing variables.

The convergence test of FG is as follows. When the Ch curve intersects the diagonal line in a diagram, if

the iterative stepwise procedure, which consists of a parallel movement from a point on the Ch curve to the diagonal line and a vertical movement from a point on the diagonal line to the Ch curve, converges on the point of intersection, then the Ch curve is decided to be convergent. If this is not the case, the curve is decided to be divergent. The above procedure can be tried easily by graphical drawing and, for example, Franks’ work may be consulted.

Finally, we should adopt the FG for which all Ch curves of tearing variables are decided to be convergent, as an element of a sequential cell FG in the next procedure.

2. Application Example

As an example, the selection of FG in the cooling tower process problem is treated. For the convenience of illustration, the fundamental equations of the n-th cell are rewritten in Table 1, where equations of mass and heat balances, mass and heat fluxes, and other equations are included.

According to a rule that mass or heat flux must be chosen as a tearing variable, we can construct the three kinds of n-th cell FGs (FG1, 2 and 3) from the combination of fundamental equations. They are shown in Fig. 1-3, where FG1 has tearing variables q_L, q_G, and N_W, FG2 has q_L, q_W, and N_W, and FG3 has q_G, q_W, and N_W.

Table 1. Fundamental Equations

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_{H_n-1} + N_{W_n} = G_{H_n} )</td>
<td>(1)</td>
</tr>
<tr>
<td>( L_{n+1} = L_n + N_{W_n} )</td>
<td>(2)</td>
</tr>
<tr>
<td>( G_{C_n} + f_{A_n-1} + q_{A_n} = G_{C_n} + f_{A_n} )</td>
<td>(3)</td>
</tr>
<tr>
<td>( C_{P_n} L_{n-1} + f_{A_n-1} ) ( = G_{P_n} L_{d_{A_n}} + q_{A_n} )</td>
<td>(4)</td>
</tr>
<tr>
<td>( N_{W_n} = k_{ga} A Z (H_{A_n} - H_n) )</td>
<td>(5)</td>
</tr>
<tr>
<td>( q_{A_n} = h_{ga} A Z (f_{A_n} - f_{A_n}) )</td>
<td>(6)</td>
</tr>
<tr>
<td>( q_{W_n} = h_{ga} A Z (f_{W_n} - f_{W_n}) )</td>
<td>(7)</td>
</tr>
<tr>
<td>( q_{W_n} = \lambda_{n} N_{W_n} )</td>
<td>(8)</td>
</tr>
<tr>
<td>( q_{L_n} = q_{G_n} + q_{W_n} )</td>
<td>(9)</td>
</tr>
<tr>
<td>( C_{H_n} = 1.0042 + 1.8828 H_n )</td>
<td>(10)</td>
</tr>
<tr>
<td>( i_C = (1.0042 + 1.8828 H_n) A_{ga} + 2498.26 H_n )</td>
<td>(11)</td>
</tr>
<tr>
<td>( f_{A_n} = (1.0042 + 1.8828 H_n) A_{ga} + 2498.26 H_n )</td>
<td>(12)</td>
</tr>
<tr>
<td>( \log (P_n) = 133.3 )</td>
<td>(13)</td>
</tr>
<tr>
<td>( H_{A_n} = 0.0222 P_n (1.013 \times 10^{-5} - P_n) )</td>
<td>(14)</td>
</tr>
<tr>
<td>( \lambda_{n} = (287.01 + 3.415 (f_{W_n}/100)^{1.15}) (374.2 - f_{W_n})^{0.365} )</td>
<td>(15)</td>
</tr>
<tr>
<td>( h_{ga} = C_{ga} K_{ga} )</td>
<td>(16)</td>
</tr>
</tbody>
</table>
The Ch curves of tearing variables based on FG1–3 may be tested. Figure 4 shows a Ch curve of tearing variable \( q_L \), corresponding to \( n=1 \) in \( q_{Ln} \), based on FG1 subject to \( q_G = 1 \), \( N_w = 0.001 \), \( t_{LB} = 20 \) and \( \Delta z = 0.001 \), which is decided to be convergent.

In Table 2, the results of convergence test of FG1–3 are prepared, where we can adopt FG1 and FG3 as an element of a sequential cell FG. The former was shown in the literature.\(^2\)

In this report, the convergence test of FG to be chosen in the procedure of a sequential cell FG construction is proposed. Similarly, it can be applied to the selection of FG in the procedure of overall FG construction.\(^3\)

Acknowledgement

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<table>
<thead>
<tr>
<th>FG</th>
<th>( q_G )</th>
<th>( q_w )</th>
<th>( N_w )</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>FG1</td>
<td>Conv</td>
<td>Conv</td>
<td>Conv</td>
<td>Conv</td>
</tr>
<tr>
<td>FG2</td>
<td>Div</td>
<td>Div</td>
<td>Div</td>
<td>Div</td>
</tr>
<tr>
<td>FG3</td>
<td>Conv</td>
<td>Conv</td>
<td>Conv</td>
<td>Conv</td>
</tr>
</tbody>
</table>

Nomenclature

\[
\begin{align*}
CH &= \text{humid heat of air} \ [\text{kJ/kg K}] \\
C_{PL} &= \text{specific heat of liquid} \ [\text{kJ/kg K}] \\
G &= \text{dry air flow rate} \ [\text{kg/m}^2 \text{s}] \\
H &= \text{humidity of air} \ [\text{kg/kg}] \\
H_s &= \text{humidity of air at interface} \ [\text{kg/kg}] \\
h_{G,a} &= \text{volumetric heat transfer coefficient in gas phase} \ [\text{kJ/m}^3 \text{K}] \\
h_{L,a} &= \text{volumetric heat transfer coefficient in liquid phase} \ [\text{kJ/m}^3 \text{K}] \\
i &= \text{enthalpy of air} \ [\text{kJ/kg}] \\
I_s &= \text{enthalpy of air at interface} \ [\text{kJ/kg}] \\
k_{G,a} &= \text{volumetric mass transfer coefficient} \ [\text{kg/m}^3 \text{s}] \\
L &= \text{liquid flow rate} \ [\text{kg/m}^2 \text{s}] \\
N_w &= \text{mass transfer rate of steam} \ [\text{kg/m}^2 \text{s}] \\
P &= \text{vapor pressure} \ [\text{Pa}] \\
q_G &= \text{heat transfer rate in gas phase} \ [\text{kJ/m}^2 \text{s}] \\
q_L &= \text{heat transfer rate in liquid phase} \ [\text{kJ/m}^2 \text{s}] \\
q_w &= \text{latent heat of vaporization} \ [\text{kJ/m}^2 \text{s}] \\
t_G &= \text{temperature of air} \ [\text{°C}] \\
t_L &= \text{temperature of liquid} \ [\text{°C}] \\
\Delta z &= \text{height of cell} \ [\text{m}] \\
\lambda &= \text{latent heat of vaporization of water} \ [\text{kJ/kg}] \\
B &= \text{tower bottom} \\
n &= \text{number of cell from tower bottom} \\
S &= \text{interface} \\
T &= \text{tower top}
\end{align*}
\]

Literature Cited