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The Simulation of the Heat Transfer trough a Shell-and-Tube Bundle Heat Exchanger

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Abstract

The paper presents the results the simulation of the shell-and-tube bundle heat exchangers. The paper is structured on fourth parts. The first part presents the process structure and the input and output variables of the heat exchanger. The second part presents a summary of the mathematical model of the shell-and-tube bundle heat exchanger. The next part there is presented the stage of the model adaptation to a particular heat exchanger. In the fourth part there are presented the obtained numerical results. The mathematical model, the solving algorithm and the calculus program have been validated by comparing the obtained numerical results for the output variables with the values presented in literature.

Key words *Heat exchanger, modeling, simulation*

Introduction

The mathematical modeling of the chemical processes represents an important problem for both the design stage and for the operation of the chemical and petrochemical plants. Among the chemical processes there is also the shell-and-tube bundle heat exchanger. Worldwide, there are avaible systems of chemical processes simulation programs, including the heat exchangers [1, 2]. These simulation programs treat globally the operation of the heat exchanger, focusing on the dimensioning of the heat transfer area in disfavor of the analysis of the operation of some already designed exchanger. In this situation, the author has investigated the possibility of the simulation of the operation of the designed heat exchanger, both for checking it and especially for the following simulation of the control systems that have within the process structure a shell-and-tube bundle heat exchanger [3, 4, 5].

The structure of the shell-and-tube bundle heat exchangers

In figure 1-a there is presented a shell-and-tube bundle heat exchanger, having fluxes in counter flow. This heat exchanger is characterized by four input and two output variables, figure 1-b [5]. The input variables are the following: T_{h1}, Q_{hot} – the inlet temperature and the hot fluid flow rate, T_{cl}, Q_{cold} – the inlet temperature and the cold fluid flow rate. The output variables are represented by T_{h2} – the outlet temperature of the hot fluid and T_{c2} – the outlet temperature of the cold fluid.

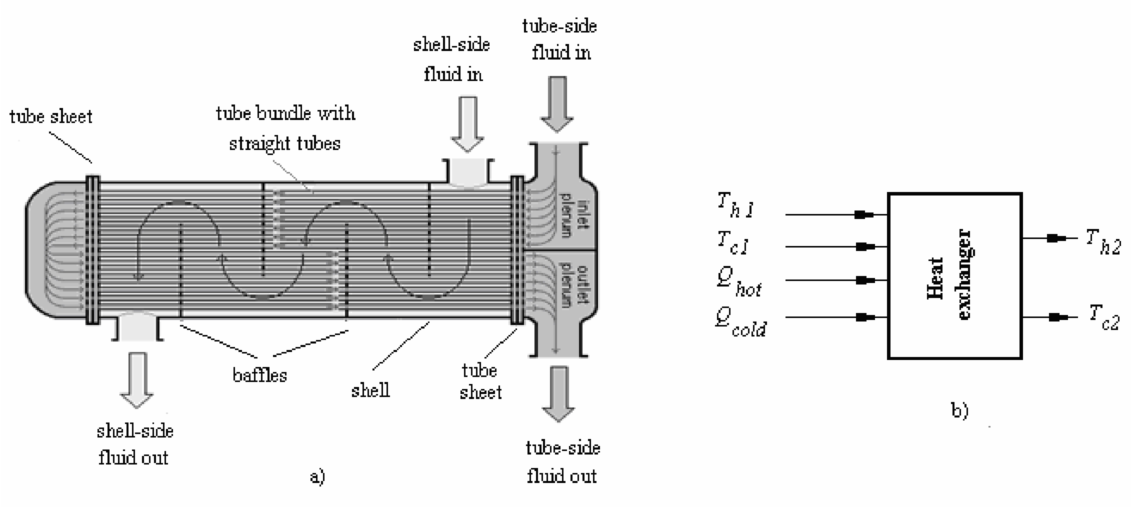

Fig. 1. The shell-and-tube bundle heat exchanger: a) cross section area; b) the process block diagram.

The mathematical modeling of the heat exchanger

The mathematical modeling of the heat exchanger presented in figure 1 has as main target the numerical calculus of the values associated to the output variables when the input variables and exchanger geometry are know. Within the research activity, the author has identified the following modeling stages [3, 5]:

a) the mathematical modeling of the heat transfer inside the tubes;

b) the mathematical modeling of the transfer in the shell;

c) the global mathematical modeling of the exchanger heat transfer.

In order to set the global mathematical model of the heat exchanger there is necessary the identification of the flows inside and outside the tubes. The mathematical model is developed according to the hypothesis that hot flow circulates outside the tubes, as position indexes *out* receive the value *hot* and the cold flow circulates inside the tubes, as the position indexes *in* receive the value *cold*.

The mathematical model of the heat exchanger is defined by the non-linear equations system

$$\begin{cases} Q_{hot}\ c_{p,hot}\ (T_{h1} - T_{h2}) = Q_{cold}\ c_{p,cold}\ (T_{c2} - T_{c1}) \\ Q_{hot}\ c_{p,hot}\ (T_{h1} - T_{h2}) = k_{ed}\ A\ \dfrac{(T_{h1} - T_{c2}) - (T_{ch2} - T_{c1})}{ln \dfrac{T_{h1} - T_{c2}}{T_{h2} - T_{c1}}} \end{cases}. \quad (1)$$

From the mathematical point of view, the system (1) represents a system of two non-linear equations

$$\begin{cases} f_1(T_{h2}, T_{c2}) = 0 \\ f_2(T_{h2}, T_{c2}) = 0 \end{cases}. \quad (2)$$

The variables of the system (2) are the outlet hot fluid temperature T_{h2} and the outlet exchanger cold fluid T_{c2}. The concrete expressions of the functions f_1 and f_2 are:

$$f_1(T_{h2},T_{c2}) = Q_{hot}\ c_{p,hot}\ (T_{h1}-T_{h2}) - Q_{cold}\ c_{p,cold}\ (T_{c2}-T_{c1}); \tag{3}$$

$$f_2(T_{h2},T_{c2}) = Q_{hot}\ c_{p,hot}\ (T_{h1}-T_{h2}) - k_{ed}\ A\ \frac{(T_{h1}-T_{c2})-(T_{h2}-T_{c1})}{ln\dfrac{T_{h1}-T_{c2}}{T_{h2}-T_{c1}}}. \tag{4}$$

The system of non-linear equations (1) can be solved using the Newton-Raphson algorithm, where the Jacobean system has the following expressions:

$$\frac{\partial f_1}{\partial T_{h2}} = -Q_{hot}\ c_{p,hot}; \tag{5}$$

$$\frac{\partial f_1}{\partial T_{c2}} = -Q_{cold}\ c_{p,cold}; \tag{6}$$

$$\frac{\partial f_2}{\partial T_{h2}} = -Q_{hot}\ c_{p,hot} - k_{ed}\ A\ \frac{-ln\dfrac{T_{h1}-T_{c2}}{T_{h2}-T_{c1}} - \dfrac{T_{h1}-T_{h2}+T_{c1}-T_{c2}}{T_{h2}-T_{c1}}}{\left(ln\dfrac{T_{h1}-T_{c2}}{T_{h2}-T_{c1}}\right)^2}; \tag{7}$$

$$\frac{\partial f_2}{\partial T_{c2}} = -k_{ed}\ A\ \frac{ln\dfrac{T_{h1}-T_{c2}}{T_{h2}-T_{c1}} - \dfrac{T_{h1}-T_{h2}+T_{c1}-T_{c2}}{T_{h1}-T_{c2}}}{\left(ln\dfrac{T_{h1}-T_{c2}}{T_{h2}-T_{c1}}\right)^2}. \tag{8}$$

The adaptation of the mathematical model

The adaptation of the mathematical model means the concrete specification of the hot fluid properties, of the cold fluid properties, as well as of the geometrical characteristics of the heat exchanger. Within the achieved study, there has been chosen a heat exchanger presented in [6]. According to the quoted source, the heat exchange takes place between the hot fluid (the kerosene), that circulates in the exchanger shell, and the cold fluid (the crude oil), that circulates in the tubes. The properties of the cold fluid, the crude oil, and of the hot fluid, the kerosene, are presented in tables 1 and table 2.

Table 1. The properties of the cold fluid (circulation inside the tubes)

Variable	Significance	Measure units	Value
$Q_{in} = Q_{cold}$	Flow rate inside the tubes	kg/h	50000
ρ_{in}	Fluid density inside the tubes	kg/m^3	820
$c_{p,in}$	Fluid specific heat inside the tubes	$J/kg\ °C$	2239
λ_{in}	Fluid heat conductivity inside the tubes	$W/m\ °C$	0.127
μ_{in}	Fluid kinematic viscosity inside the tubes	$kg/m\ s$	18×10^{-4}
T_{c1}	Inlet temperature of (cold) fluid in the tubes	$°C$	103

Table 2. The properties of the hot fluid (circulation outside the tubes)

Variable	Significance	Measure units	Value
$Q_{out} = Q_{hot}$	Fluid flow rate outside tubes	kg/h	163000
ρ_{out}	Fluid density outside tubes	kg/m^3	660
$c_{p,out}$	Fluid specific heat outside tubes	$J/kg\,°C$	2602
λ_{out}	Fluid heat conductivity outside tubes	$W/m\,°C$	0.1364
μ_{out}	Fluid kinetic viscosity outside tubes	$kg/m\,s$	3×10^{-4}
T_{h1}	Inlet temperature fluid (cold) in shell	$°C$	180

The geometrical characteristics and the values of some parameters of the heat exchanger are presented in table 3 and 4.

Table 3. The heat characteristics associated to the heat exchanger

Variable	Significance	Measure units	Value
λ_t	Tube heat conductivity (tubes of carbon steel)	$W/m\,°C$	40
$R_{d,in}$	Specific heat resistance of the deposit inside tubes	$m^2\,°C/W$	0.0011
$R_{d,out}$	Specific heat resistance of the deposit outside tubes	$m^2\,°C/W$	0.0004

Table 4. The geometrical characteristics of the heat exchanger

Variable	Significance	Measure units	Value
L	Tube length	m	6
N_p	Number of passes of tubes	-	2
n_t	Number of tubes	-	900
n_f	Number of tubes in window	-	112
d_i	The interior diameter of tubes	mm	20
d_e	The exterior diameter of tubes	mm	25
D_i	Shell diameter	m	1.1
D_f	Window diameter	m	1.06
D_s	Cavil diameter	m	1.095
x	Distance between cavils	m	0.4
s	Side of equilateral triangle of the tubes	mm	32
d_o	Holes diameter	m	0.026
φ	The angle at the center of the chord of cavil	°	106
N_{sl}	Number of pairs of scaling longitudinal cavils	-	2
N_{if}	Number of the tubes rows placed between the windows	-	24
h	Cavil height	m	0.88

The simulation of the heat exchanger using Unisim program

The program ***Unisim Shell Tube Exchanger Modeler R380*** is used to modeling and to simulating the shell-and-tube bundle heat exchangers. The most important constructive classification of the heat exchanger with shell and tube has proposed by **T**ubular **E**xchanger

Manufacturers **As**sociation (abbreviation **TEMA**) [7]. This classification uses the following criterions [8]:

a) the front end head construction;
b) the circulation type of the stream between the tubes and shell;
c) the type of the front end head.

The author has studied the main facilities of the ***Unisim Shell Tube Exchanger Modeler R380*** program and has identified the following calculus stages:

1. Select the ***Simulation*** function of ***Start Up*** section.
2. Select the geometrical specifications of the heat exchanger in the ***Exchanger General*** section. The heat exchanger has the following characteristics: the front end head type is demountable (**TEMA A**), the shell type has two tube pass into shell (**TEMA F**), the rear end head type with demountable mobile head (**TEMA S**), the shell orientation is horizontal and the side for hot stream is the shell side. An image of this stage is presented in figure 2.
3. Select the section ***Tube Details*** for specification of the geometrically tubes characteristics.
4. Select the section ***Transverse Baffles*** for specification of the geometrically characteristics of the baffles. The flow section between the baffle and the shell is calculated using the relations presented in table 5.
5. The characteristics of the cold and the hot stream are specificities into ***Physical Proprieties*** section.

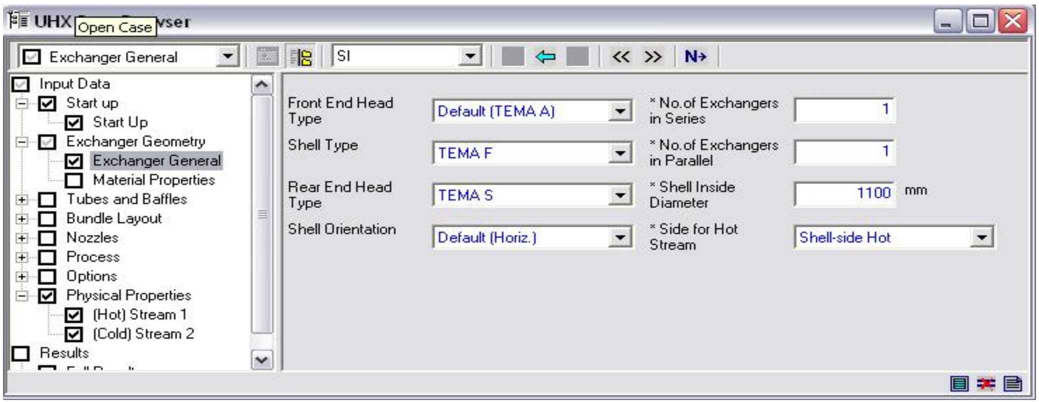

Fig. 2. The geometrical specifications of the heat exchanger.

Table 5. The formulas used for the flow section between the baffle and the shell

Variable	Formula
Circle area	$A_c = \pi \cdot \frac{D^2}{4}$
Area of the circle segment with α angle	$A_\alpha = \frac{\alpha}{360} \cdot \frac{\pi \cdot D^2}{4}$
Triangle area	$A_t = \frac{D^2}{4} \cdot \sin\left(\frac{\alpha}{2}\right) \cdot \cos^2\left(\frac{\alpha}{2}\right)$
Flow section area	$A_{cut} = A_\alpha - A_t$
Flow section percent	$P_{cut} = \frac{A_{cut}}{A_c} \cdot 100$

Numerical results

The author has simulate the heat transfer trough shell and tube heat exchanger using two ways: first way is dedicated to solve the mathematical model (1) and second way contains the heat exchanger simulation using the ***Unisim Shell Tube Exchanger Modeler R380.***

For solve the mathematical model (1), the author has elaborate a specially program, which use the Newton – Raphson algorithm for solving the non-linear equations systems [9]. There has implemented two versions of simulation programs: one version use the analytically Jacobean matrix and the second version use the numerically Jacobean matrix evaluation [4]. In table 6 there are presented comparatively the results obtained for the solving of the mathematical model of the heat exchanger by means of the two algorithms.

Table 6. The Newton - Raphson comparative results

Iteration	**Equation index**	**Newton-Raphson algorithm based on analytical derivatives**		**Newton-Raphson based on numerical derivatives**	
		$x \times 10^{-2}$	f	$x \times 10^{-2}$	f
0	1	1.3701357466	7.0651772244E+05	1.3701357466	7.0651772244E+05
	2	1.1701357466	2.5760903814E+05	1.1701357466	2.5760903814E+05
1	1	1.3786567675	0.0000000000E+00	1.3880450337	-2.7160644531E-03
	2	1.1896271727	1.8637047361E+05	1.1860703994	2.3748612976E+03
2	1	1.3837998035	0.0000000000E+00		
	2	1.1876787178	8.5532275970E+04		

The second way to simulate the heat exchanger simulation has used the ***Unisim Shell Tube Exchanger Modeler R380***. The results obtained with this simulation program are presented in figure 3.

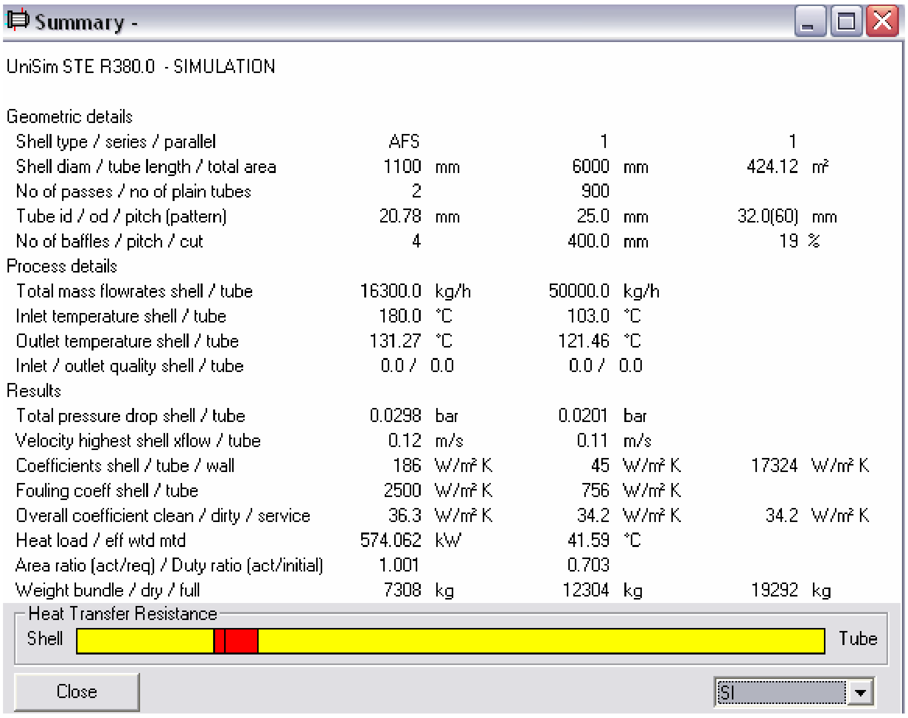

Fig. 3. The numerical results obtained by Unisim Shell Tube Exchanger Modeler R380

In table 7 are presented the comparative output temperatures of the heat exchanger. There are three value sources:

a) the original example, presented in [6];

b) the results obtained by solve the mathematical model (1);

c) the results obtained by use the Unisim Shell Tube Exchanger Modeler R380 simulation program.

Theses results validate the mathematical model proposed by the author and the elaborated simulation program. In future, the mathematical model will be used to simulate the control systems what contain the heat exchanger.

Table 7. The comparative results of the heat exchanger simulation

Simulation result	**Outlet hot temperature [ºC]**	**Outlet cold temperature [ºC]**
Original example [6]	140.0	118.0
Simulation on the mathematical model (1)	138.4	118.7
UNISIM simulation	131.3	121.5

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Simularea schimbătoarele de căldură tubulare cu şicane şi manta

Rezumat

Schimbătoarele de căldură sunt aparate de transfer termic intens folosite in industria chimică şi petrochimică. Dintre schimbătoarele de căldură, un loc important îl reprezintă schimbătoarele de căldură cu fascicul tubular în manta. Cercetările autorului in domeniul modelării matematice a transferului termic pentru acest tip de schimbător de căldură au urmărit două direcții. Prima direcție este reprezentată de elaborarea unui model matematic destinat simulării acestui tip de schimbător. Cea de a doua direcție de cercetare a fost axată pe utilizarea mediului UNISIM pentru simularea schimbătoarelor de căldură cu fascicul tubular în manta. Rezultatele numerice obținute prin utilizarea modelului matematic dezvoltat de autor şi cele furnizate de mediul de simulare au fost comparate cu cele din literatură. Valorile numerice obținute au validat modelul matematic propus de autor.