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Some aspects of plate number estimation of plate heat exchangers (PHEs). A case study

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Abstract. For the proper estimation of the plate number (N) of a plate heat exchanger (PHE) – in addition to the flow rates and thermophysical properties of fluids –, an appropriate correlation is needed for convective heat transfer coefficient (α) calculation. When one does not have a criterial equation for the corresponding plate shape, we propose a selecting method for α. With the suggested relationships from literature, we calculate the plate number of a geometrically known, similar heat duty PHE and choose those relationships that give the same plate number with the known heat exchanger. In our case study, the plate number determined by any of the screened equations for whole milk preheating has almost the same value (n = 10 ± 1) regardless of the method used to solve the PHE model (plate efficiency and $N_{converg}$ or $K_{converg}$ convergence methods). For liquids' thermophysical property estimation, we recommend averaging the values given by equations from literature, followed by equation fitting.

Keywords and phrases: milk, thermophysical properties, plate heat exchangers, plate number estimation

1. Introduction

The main heat exchanger type in food industry is the plate heat exchanger (PHE), used for the heating or cooling of media with good rheological properties and with low solid content, to avoid solid deposition on the surface (usually Newtonian liquids as milk, various fruit juices, high-temperature cooking oils, cleaning and process waters, etc.) (*Mariott*, 1979; *Stoica et al.*, 2007; *Singh & Heldman*, 2013; *Kakaç et al.*, 2020). Hot water or steam (heating medium), chilled water, cooling water, brine or propylene glycol water solutions (cooling medium) are used as thermal agent (*Macovei*, 2001; *Kakaç & Liu*, 2002; *Heldman*, 2007; *Thulukkanam*, 2013). The PHE's operation is characterized by a continuous steady state (*Shah & Sekulić*, 2002; *Singh & Heldman*, 2013; *Roetzel et al.*, 2020), but it can also be used for setting batch temperature (cooling/heating). Its widespread use is mainly due to its high heat transfer coefficient and the resulting low specific space requirements (*Stephan*, 2010; *Wang & Sunden*, 2007; *Thulukkanam*, 2013; *Neagu et al.,* 2014). An advantage of gasketed heat exchangers is cleanability (*Fonyó & Fábry*, 2004; *Neagu et al.*, 2014) and, perhaps more importantly, the variability of connection configurations (*Fonyó & Fábry*, 2004; *Macovei*, 2001) as: single-pass parallel switching (mainly countercurrent) (*Chisholm & Wanniarachchi*, 1999; *Singh & Heldman*, 2013), possible multipass-flow (serial switching) (*Macovei*, 2001), and, of course, multiple parallel and serial switching could be combined (*Maroulis & Saravacos*, 2003). The brazed exchangers have constant plate numbers, and the plates are joined by pressure or thermal welding, this type being used mainly in building central heating systems.

In the food industry, the almost exclusively (excepted high-pressure, e.g. water-air heaters) utilized PHE types are gasketed PHEs. Their advantage consists in their modular structure, wherefore the heat exchange surface could be easily increased, by supplementation of the plate number, and their cleaning is more simple and complete, in agreement with food industry requirements. Furthermore, this structure made suitable the compact assembly of plate pasteurizer, with heat recovery zones, as required in dairy and fruit industries. In the interstices between the plates, the flow is usually turbulent since the interstices are tight (usually 2–5 mm), and the plate surfaces are corrugated to assure the breaking of current lines, to increase the surface area, and to improve the plate's mechanical strength. The geometry, number, angle, and size of the corrugation are determinant for flow direction and local velocity (*Focke et al.*, 1985; *Heavner et al.*, 1993; *Muley & Manglik*, 1999; *Gut et al.*, 2004; *Kakaç et al.*, 2020). Therefore, the use of dimensionless number relations (criterial equations) to determine heat transfer requires great attention as their validity is restricted to the particular plate type. Nevertheless, in the literature, we can find criterial equations considered generally applicable, independent from plate type (*Kumar*, 1984; *Fonyó & Fábry*, 2004; *Macovei*, 2001; *Kakaç & Liu*, 2002; *Stoica et al.* 2007). The main goal of this article is to examine the general validity of these relations; as a case study, a milk pasteurizer pre-heating zone was chosen.

The engineering tasks related to the PHEs can be divided into several groups (*Stoica et al.*, 2007):

a) Assigning the appropriate heat exchanger type and size to a given heat power duty, sizing design, i.e. determination of the heat exchanger surface;
b) Checking the suitability of the heat exchanger for a certain duty, when the heat transfer surface area is given, and the flow parameters that assure the outlet temperature of the target fluid need to be determined;
c) Estimation of the outlet temperature of a medium with given flow characteristics and known inlet temperature in a heat exchanger of a defined configuration.

To achieve this goal, some basic knowledge is required (*Haslego & Polley*, 2002; *Faulkner*, 2013; *Dvorak & Vit*, 2017; *Ezgi*, 2017), namely:

a) The properties of the heat exchange media, influencing the impulse and heat transfer (density, dynamic or kinematic viscosity, thermal conductivity, and specific heat capacity). It is recommended to know the temperature dependence of the thermophysical properties;
b) The proper mathematical model of the heat exchanger;
c) The values of the geometric size of the plate and the thermal conductivity of the structural material of the plates;
d) The effect on heat transfer rate of the interaction between the flowing media and the structural material of the heat exchanger (fouling or deposition effect).

Moreover, it is important to know specific solving methods of the heat exchanger model because the model is usually underdetermined as it contains more variables than relationships (*Maroulis & Saravacos*, 2003; *Shah & Sekulić*, 2002; *Stoica et al.*, 2007; *Mota et al.*, 2015).

2. Materials and methods

In order to select the proper criterial equations from the literature and to determine the appropriate thermophysical properties required for using them in the design process, we used the method described below.

The thermophysical properties were plotted as a function of temperature (from the tabular data or fitted functions), excluding those that did not show the same trend as the majority, and then the average was calculated taking into account the remaining values; finally, a function was fitted on the average values. The fitted function was the same form as given in the literature for the specific thermophysical property (e.g. polynomial or exponential type relations).

To select the appropriate criterial equation for the heat transfer modelling of the PHE, the plate number required to perform the given thermal duty was determined using three resolution methods: plate number convergence ($N_{converg}$), overall heat transfer convergence ($K_{converg}$), or thermal efficiency (NTU-ε) – for a PHE of known size and thermal duty. Criterial correlations that result in plate number values equal to or close to the real heat exchanger were considered suitable for the proposed design task, namely for the determination of the plate number of the milk pre-heater PHE.

For modelling purposes, Excel software (Microsoft) and for graphical representation Statistica 8.0 (Statsoft, Inc) was used.

Estimation of the thermophysical properties of media involved in the heat exchange

The properties of the various heating and cooling media (water, water-ethylene glycol, water-propylene-glycol, steam) can be found quite accurately in the literature, but mostly in tabulated form (not as a correlation). From this tabular data, by means of different commercial software, it is usually easy to establish good correlations, which will be suitable in mathematical models.

In the case of liquid foods, it is a little more difficult to find the right correlations given the multitude of ingredients and interactions between them, which modify the thermo- and hydrodynamic (thermophysical) properties (*Rohm et al.*, 1996; *Minim et al.*, 2002; *Lewis*, 2006; *Heldman*, 2007; *Munir et al.*, 2016). Besides the widely utilized and accepted method of Choi and Okos (1986) based on the weighted average of the six food component properties (carbohydrate, protein, fat, mineral salt, fibre, and water), there is a great deal of other literature data on specific liquid foods as milk and other liquid dairy products. Furthermore, the Choi–Okos equations do not include viscosity, which property is crucial for heat transfer. Thermophysical property functions have a great variety as they do not always take into account all the constituents. The properties are expressed in function of different main component (fat, protein, total non-fat solid, or total solid content) molar or mass concentrations and temperature (*Gavrilă et al.*, 2002; *Apetrei et al.*, 2002; *Madoumier et al.*, 2015). Regardless of the chosen equation, it is always highly recommended to validate them by measurements or to compare the calculated results with reliable data. In every case when we start to estimate the properties from a very wide variety of regression equations with variable precision and validity range, a question arises: which one should be applied in the model?

To resolve this uncertainty, we propose an approximation method that assumes the following steps: we plotted the data from the correlations (as a function of temperature) found in literature (see *tables 1a–d*) and excluded the equation(s) showing markedly different values, whereafter we fitted a curve on the average value of the property. The method is presented only for whole milk, but the calculation was made also for other liquid milk varieties by using supplementary relations (*Hu et al.*, 2009) such as skim and standardized milk (data not shown). *Tables 1a–d* contain the relations from literature for the thermophysical properties (density, dynamic viscosity, heat capacity, thermal conductivity) of whole milk.

Table 1a. Equations for milk density estimation

No.	$\boldsymbol{\rho}$ **(kg · m^{-3})**	**References**
1.	$\rho = 1040.51 - 0.2665\,t - 2.307\cdot 10^{-3}\,t^2 -$ $-(F\%)\cdot(0.967 + 9.69\cdot 10^{-3}\,t - 4.781\cdot 10^{-5}\,t^2)$	*Kessler*, 2002 *Bertsch & Cerf*, 1983
2.	$\rho = 1185.64 - 0.341(t + 273.15) - 58.239\,X_w - 58.107\,X_F$	*Minim et al.*, 2002
3.	$\rho_f = 925.56 - 0.41757\,t$ $\rho_p = 1329.0 - 0.5184\,t$ $\rho_c = 1599.1 - 0.31046\,t$ $\rho_m = 2423.8 - 0.28063\,t$ $\rho_w = 1\,000.0791 + 0.008380\,t - 0.00561612\,t^2 + 0.0000135933\,t^3$ $\rho_{milk} = \dfrac{1}{\dfrac{X_f}{\rho_f} + \dfrac{X_p}{\rho_p} + \dfrac{X_c}{\rho_c} + \dfrac{X_m}{\rho_m} + \dfrac{X_w}{\rho_w}},$ x_i – mass fractions of: fat (f), protein (p), carbohydrate (c), minerals (m), and water (w) $\rho_{milk} = \sum_{i=1}^{5} \rho_i y_i$. $where$: $y_i = \dfrac{\frac{x_i}{\rho_i}}{\sum_1^5 \frac{x_i}{\rho_i}}$. y_i – volumetric fraction.	Engineering Toolbox Database
4.	$\rho = 1042.01 - 0.37\,t - 3.6\cdot 10^{-4}\,t^2$, for whole milk	*Bon et al.*, 2010 *Munir et al.*, 2016
5.	$\rho = 1035 - 0.358\,t + 0.0049\,t^2 - 0.00010\,t^3$	*Rao et al.*, 2005
6.	$\rho = 1028.9 - 0.195\,t + 1.432\,X_F$ Fat content: 3…6%	*Watson & Tittsler*, 1961
7.	$\rho = 1038.2 - 0.17\,t - 0.003\,t^2 + \left(133.7 - \dfrac{475.5}{t}\right)\cdot X_F$	*Phipps*, 1969
8.	$\rho_{20\,°\mathrm{C}} = \dfrac{1000}{0.123\cdot X_F + 0.9665}$	*McCarthy & Singh*, 1990
9.	$DM\,(\%) = 400\cdot(d-1) + 1.21\cdot(\%F) + 0.72$ DM(%) – dry matter, %, $\%F$ – fat content, $d = \dfrac{\rho_{milk}}{\rho_{water}}$	*Lewis*, 2006

Table 1b. Equations for milk viscosity estimation

<table>
<tr><th>No.</th><th>η (mPa · s)</th><th>References, temperature interval</th></tr>
<tr><td>1.</td><td>$\eta = Exp[(3.03 \cdot 10^{-5}\, t^2 - 0.01813\, t + 0.609) +$
$+(2.3 \cdot 10^{-4}\, t^2 + 5.49 \cdot 10^{-2}\, t + 0.206) \cdot X_F +$
$+(2.5 \cdot 10^{-3}\, t^2 + 0.629\, t + 5.42) \cdot {X_F}^2]$</td><td><i>Kessler</i>, 2002</td></tr>
<tr><td>2.</td><td>$ln\eta = (3.92 \cdot 10^{-5}\, t^2 - 1.951 \cdot 10^{-2}\, t + 0.666)$
$+ (-9.53 \cdot 10^{-4}\, t^2 + 0.1674\, t - 4.37) \cdot X_F$
$+ (9.75 \cdot 10^{-3}\, t^2 - 1.739\, t + 98.3) \cdot {X_F}^2$</td><td><i>Bertsch & Cerf</i>, 1983;
70… 135 °C</td></tr>
<tr><td>3.</td><td>$\eta = (0.9565 - 1.3004 \cdot 10^{-3}\, t + 1.958 \cdot 10^{-4}\, t^2)$
$+ (47.66 - 1.144 \cdot t + 7.2642 \cdot 10^{-3}\, t^2) \cdot X_F$</td><td><i>Munir et al.</i>, 2016</td></tr>
<tr><td>4.</td><td>$ln\eta = (A_o + A_1 \cdot t + A_2 \cdot t^2) + (B_o + B_1 \cdot t + B_2 \cdot t^2) \cdot (\%F) +$
$(C_o + C_1 \cdot t + C_2 \cdot t^2) \cdot (\%DM)^2$
<table>
<tr><th>i</th><th>A_i</th><th>B_i</th><th>C_i</th></tr>
<tr><td>0</td><td>0.249</td><td>0.02549</td><td>0.000543</td></tr>
<tr><td>1</td><td>-0.013</td><td>-0.000098</td><td>-0.0000139</td></tr>
<tr><td>2</td><td>0.000052</td><td>0.0000004</td><td>0.000000117</td></tr>
</table></td><td><i>Fernandez-Martin</i>, 1972;
0… 80 °C</td></tr>
<tr><td>5.</td><td>$A_F = 3.46 - 0.025\, t + 1.6 \cdot 10^{-4}\, t^2$
$A_P = 15.367 - 0.175\, t + 0.0017\, t^2$
$A_C = 3.35 - 0.0238\, t + 1.25 \cdot 10^{-4}\, t^2$
$\eta_{milk} = \eta_{water} \cdot Exp\left(\frac{\sum_1^3 A_i X_i}{X_{H_2O}}\right)$</td><td><i>Morison et al.</i>, 2013</td></tr>
<tr><td>6.</td><td>$ln\eta = \frac{2721.5}{273 + t} + 0.1\,(\%F) - 8.9$</td><td><i>Bakshi & Smith</i>, 1984; 0…. 30 °C</td></tr>
<tr><td>7.</td><td>$lg\eta = (1.2876 + 11.0710^{-4}\, t) \cdot \left(X_F + X_F^{5/3}\right) + 0.7687 \frac{1000}{273 + t}$
$- 2.437$</td><td><i>Phipps</i>, 1969;
40… 80 °C</td></tr>
<tr><td>8.</td><td>$\eta = \frac{6.45}{t^{0.85}} \cdot exp(0.05 + 0.08 \cdot (\%\, DM))$</td><td><i>Ganea & Cojoc</i>, 2011</td></tr>
<tr><td>9.</td><td>$\eta = 2.82 - 4.58 \cdot 10^{-2}\, t + 2.83 \times 10^{-4}\, t^2$,
for whole milk</td><td><i>Bon et al.</i>, 2010</td></tr>
<tr><td>10.</td><td>$\eta = 0.96 + 0.058(\%F) + 0.156(\%P)$</td><td><i>Rohm et al.</i>, 1996;
at 25 °C</td></tr>
</table>

Table 1c. Equations for specific heat capacity estimation

No.	$\mathbf{c_p}\ (\mathbf{J \cdot kg^{-1} \cdot K^{-1}})$	References
1.	$c_p = 3744.48 + 1.15\,t + 0.00393\,t^2$	*Bon et al.*, 2010 *Munir et al.*, 2016
2.	$c_p = 1401.7\ + 2.1 \cdot (t + 273.15) + 2181.6 \cdot X_w - 1.743 \cdot X_F$	*Minim et al.*, 2002
3.	$c_{p\,(P)} = 2008.2 + 1.2089\,t - 1.3129 \cdot 10^{-3}\,t^2$ $c_{p\,(F)} = 1984.2 + 1.4733\,t - 4.8008 \cdot 10^{-3}\,t^2$ $c_{p\,(C)} = 1548.8 + 1.9625\,t - 5.9399 \cdot 10^{-3}\,t^2$ $c_{p\,(M)} = 1092.6 + 1.8896\,t - 3.6187 \cdot 10^{-3}\,t^2$ $c_{p\,(H_2O)} = 4176.2 - 0.0980864\,t + 5.4731 \cdot 10^{-3}\,t^2$ $c_{p\,milk} = \sum_{1}^{5} c_{p(i)} \cdot X_i$	*Choi & Okos*,1986
4a.	$c_p = 1424\,X_c + 1549\,X_P + 1675\,X_F + 4187\,X_w$	*Heldman & Singh*, 1981
4b.	$c_p = 4187 \cdot X_w + (1373 + 11.3\,t) \cdot (1 - X_w)$	*Hwang & Gunasekaran*, 2003
5.	$c_p = 3692 + 2.976\,t$	*McCarthy & Singh*, 1990
6.	$c_p = 41.88 \cdot (\%H_2O) + (13.71 + 0.1129 \cdot t) \cdot (\%DM)$	*Fernandez-Martin*, 1972
7.	$c_p = 4190 - 2765\,X_C - 125\,X_P - 335\,X_F$	*Ganea & Cojoc*, 2011

Table 1d. Equations for heat conductivity estimation

No.	$\boldsymbol{\lambda}\ (\mathbf{W \cdot m^{-1} \cdot K^{-1}})$	References
1.	$\lambda = (5.9 \cdot 10^{-1} + 1.2 \cdot 10^{-3}\,t)(1 - 7.8 \cdot 10^{-3}\,X_{DM})$	*More & Prasad*, 1988
2.	$\lambda = (326.58 + 1.0112\,t - 3.37 \cdot 10^{-3}\,t^2) \cdot (0.46 + 0.54\,X_w) \cdot 0.00173$	*Riedel*, 1949
3a.	$\lambda = -0.2145 + 0.0014 \cdot (t + 273.15) + 0.4171\,X_w - 0.092\,X_F$	*Minim et al.*, 2002, *Munir et al.*, 2016 (from Minim data)
3b.	$\lambda = 0.0163 + 1.4 \cdot 10^{-3} \cdot (t + 273.15) + 0.2\,X_w + 0.04\,X_F$	
3c.	$\lambda = 0.5279 + 0.00213\,t - 7.32 \cdot 10^{-6}\,t^2 \cdot (1 - 0.843\,X_F + 0.0019\,t)$	
4.	$\lambda = 0.49 + 2.23 \times 10^{-3}\,t - 1.08 \times 10^{-5}\,t^2$ (whole milk)	*Bon et al.*, 2010
5.	$\lambda = (0.565 + 0.0018\,t - 0.0000058\,t^2) \cdot [1 - 0.005 \cdot (10 + 2 \cdot \%F) \cdot R]$ R- concentrating factor (DM in concentrate/DM in whole milk)	*McCarthy & Singh*, 1990

No.	$\lambda\ (\mathbf{W \cdot m^{-1} \cdot K^{-1}})$	**References**
6.	$\lambda_P = 0.17881 + 1.1958 \cdot 10^{-3}\, t - 2.7178 \cdot 10^{-6}\, t^2$	*Choi & Okos*, 1986
	$\lambda_f = 0.18071 - 2.7604 \cdot 10^{-4}\, t - 1.7749 \cdot 10^{-7}\, t^2$	
	$\lambda_c = 0.20141 + 1.3874 \cdot 10^{-3}\, t - 4.3312 \cdot 10^{-6}\, t^2$	
	$\lambda_m = 0.32962 + 1.4011 \cdot 10^{-3}\, t - 2.9069 \cdot 10^{-6}\, t^2$	
	$\lambda_w = 0.57109 + 1.7625 \cdot 10^{-3}\, t - 6.7036 \cdot 10^{-6}\, t^2$	
	$\lambda_{milk} = \sum_{1}^{5} \lambda_i y_i.\quad \lambda_{milk} = \frac{1}{\sum_i^5 \frac{y_i}{\lambda_i}}.\quad y_i = \frac{\frac{X_i}{\rho_i}}{\sum_1^5 \frac{X_i}{\rho_i}}$	

The mathematical model of the heat exchangers

The mathematical model of PHE is based on the steady state heat transfer (*Fonyó* & *Fábry*, 2004; *Singh* & *Heldman*, 2013). Taking into account the heat transport for elementary surface, the fundamental equation of plate heat exchangers can be established:

$$\dot{Q} = K \cdot K \cdot A \cdot \Delta T_m,\ \mathrm{W} \tag{1}$$

The transferred heat flux ($\dot{Q}$) is determined by the surface (A), overall heat transfer coefficient (K), and the mean logarithmic temperature (ΔT_m).

$$\Delta T_m = \frac{(T_1^o - T_2) - (T_1 - T_2^o)}{ln\frac{T_1^o - T_2}{T_1 - T_2^o}} \tag{2}$$

The overall heat transfer coefficient (K) can be calculated in function of convective heat transfer coefficient, the heat conductivity of plate material (stainless steel), and the fouling heat resistance:

$$\frac{1}{K} = \frac{1}{\alpha_1} + r_1 + \frac{\delta}{\lambda} + r_2 + \frac{1}{\alpha_2}, \tag{3}$$

where: α_1, α_2 are convective heat transport coefficients, W/(m^2·K), r_1, r_2 is the fouling resistance, and (m^2·K/W), $\frac{\delta_p}{\lambda_p}$ is the heat resistance of the plate material, (m^2·K/W).

For the estimation of convective heat transfer coefficient, the well-known relation can be used:

$$Nu = C \cdot Re^m Pr^n \Gamma^p, \tag{4}$$

where: C, m, n, p are coefficients depending on the flow characteristics of the two fluids and on the configuration of plates (see the appendices).

Empirical data are used to estimate the heat resistances of the fouling deposits. This is shown in *Table 2*.

Table 2. Heat resistance of deposits of different heat transfer agents (Fonyó & Fábry, 2004)

Heat transfer agent	**r, m²·K/W**	**Heat transfer agent**	**r, m²·K/W**
Dirty water	0.00009-0.00017	Clean water	0.000017-0.000043
Sugar juice	0.00013-0.00017	Fermented juice	0.000043
Brine	0.000086	Beer	0.00001-0.00003
River water	0.00004-0.00009	Milk	0.00001-0.00003

In order to determine the convective heat transfer coefficients, in addition to the liquid properties, it is necessary to know the nature of the flow regime, which is in fact determined by the geometry of the plates (plate corrugation and width, channel width) as well as the mass flow rates. The mathematical model of the PHE is shown in *Table 3*.

Table 3. Mathematical model for the PHEs' plate number calculation

Plate length, m	L
Plate width, m	W
Plate distances (gap width), m	δ
Plate surface, m²	$A_{plate} = L \cdot W \cdot \varphi; \quad \varphi = 1.15 - 1.2$
Interplate flow section area, m²	$S = W \cdot \delta$
Hydraulic diameter, m	$d_e = \dfrac{2 \cdot \delta}{\varphi}$
Released heat flow, W	$\dot{Q}_1 = m_{\tau 1} \cdot c_{p1} \cdot (T_1^o - T_1)$
Received heat flow, W	$\dot{Q}_2 = -m_{\tau 2} \cdot c_{p2} \cdot (T_2^o - T_2)$
Transferred heat, W	$\dot{Q} = K \cdot A \cdot \Delta T_m$ $A = N \cdot A_{plate} \cdot \varphi = N \cdot W \cdot L \cdot A_{plate} \cdot \varphi$
Flow velocities, m/s	$w_1 = \dfrac{m_{\tau 1}/\rho_1}{n_g - k \cdot A_k}, \; w_2 = \dfrac{m_{\tau 2}/\rho_2}{n_g - k \cdot A_k},$ n_g – gap number for one fluid

Reynolds numbers	$Re_1 = \frac{\rho_1 \cdot w_1 \cdot d_e}{\eta_1}, Re_2 = \frac{\rho_2 \cdot w_2 \cdot d_e}{\eta_2}$
Nusselt numbers	$Nu_1 = C \cdot Re_1^m Pr_1^n, Nu_2 = C \cdot Re_2^m Pr_2^n$
Convective heat transfer coefficients, W/(m²·K)	$\alpha_1 = \frac{Nu_1 \cdot \lambda_1}{d_e}, \alpha_2 = \frac{Nu_2 \cdot \lambda_2}{d_e}$
Overall heat transfer coefficients, W/(m²·K)	$K = \left(\frac{1}{\alpha_1} + r_1 + \frac{\delta}{\lambda} + r_2 + \frac{1}{\alpha_2}\right)^{-1}$
Calculated plate number from thermal relations	$N_t = \frac{\dot{Q}_{1/2}}{K \cdot \Delta T_m \cdot A_{plate}}$

The algorithms of several solution methods of the selected models (*Table 3*) for particular cases are presented below (*Jackson* & *Troupe*, 1966; *Okada*, 1972; *Kreith*, 1999; *Kakaç* & *Liu*, 2002; *Shah* & *Sekulić*, 2002; *Wright* & *Heggs*, 2002, *Wang et al.*, 2007; *Singh* & *Heldman*, 2013; *Thulukkanam*, 2013; *Faulkner*, 2013; *Dvorak* & *Vit*, 2017):

Plate number convergence ($N_{converg}$) steps:

1. Calculation of the thermal balance and the thermophysical parameters to determine the transferred heat and the outlet temperatures;
2. Calculation of the logarithmic mean temperature;
3. Giving an initial value for interplate gap number for a single fluid;
4. Determination of the flow velocities for both fluids, then calculation of the Reynolds numbers;
5. Determination of the values of thermophysical properties for the two fluids at their mean temperature followed by the calculation of the Nusselt numbers with the adopted criterial equation;
6. Calculation of the individual heat transfer coefficients for both fluids, using the Nusselt numbers, followed by the determination of the overall heat transfer coefficient for the PHE;
7. Calculation of heat transfer area followed by the determination of plate number (the fractional result needs rounding up);
8. Determination of channel numbers for each fluid. Impair plate number gives individual equal channel number for the two fluids;
9. Comparison of the resulted channel number with the initially chosen value in point 3. When these two values are equal, the real plate number is found; otherwise, the process will be restarted from point 3.

Overall heat transfer coefficient convergence ($K_{converg}$) steps:

1. Choosing the value for overall heat transfer coefficient (K value);
2. Calculation of the heat transfer area followed by the determination of plate number (the fractional result needs rounding up);
3. Determination of channel numbers for each fluid. For odd plate numbers, the number of channels for the two fluids will be equal, while for even plate numbers, the number of channels will differ by one unit;
4. Calculation in cascade of the fluid flow velocities, Re numbers, Nu numbers, and individual heat transfer coefficients;
5. Calculation of the value for K;
6. Comparison of the K value with the initially chosen K value in point 1. When these two values are equal, the real K value is found; otherwise, the process will be restarted from the beginning, setting the calculated K value as initial value, and the whole calculus will be repeated.

As the method converges, the final value of K will be obtained in several cycles.

Iterative calculation for thermal efficiency method (NTU-ε) with number of plate convergence

1. Determination of the changed heat:

   $$\dot{Q}_{ch} = m_{\tau 1} \cdot \left(c_{p1}^{o} \cdot T_1^o - c_{p1} \cdot T_1\right) \text{ or: } \dot{Q}_{ch} = -m_{\tau 2} \cdot \left(c_{p2}^{o} \cdot T_2^o - c_{p2} \cdot T_2\right);$$

2. Calculation of the unknown temperatures (if any), the average temperatures, drawing the temperature profile, the temperature diagram, and, finally, determination of the logarithmic average temperature difference:

   $$(\Delta T_{m)}: \bar{T}_1 = 0.5 \cdot (T_1^o + T_1),\ \ \bar{T}_2 = 0.5 \cdot (T_2^o + T_2), \bar{T}_{wall} = 0.5 \cdot (\bar{T}_1 + \bar{T}_2);$$

3. Determination of the values of thermophysical (ρ, c_p, λ, η) properties for the two fluids at their mean temperature;
4. Calculation of the water equivalent of the two fluids: $C_1=m_{\tau 1}c_{p1}$, $C_2=m_{\tau 2}c_{p2}$;
5. Calculation of the ratio of the water equivalent of the two fluids: $R = \frac{C_{min}}{C_{Max}}$;
6. Calculation of the ratio of the thermal efficiency of the PHE:

   $$\varepsilon = \frac{C_1(T_1^o - T_1)}{C_{min}(T_1^o - T_2^o)} = -\frac{C_2(T_2^o - T_2)}{C_{min}(T_1^o - T_2^o)};$$

7. Calculation of the number of transfer units (NTU): $NTU = \frac{ln\frac{1-\varepsilon R}{1-\varepsilon}}{1-R}$;
8. Choosing the value for plate number followed by calculation of the gap numbers for both fluids;

9. Calculation in cascade of the fluid flow velocities, Re numbers, Nu numbers, and individual heat transfer coefficients;
10. Calculation the value for overall heat transfer coefficient (K), taking into account the fouling resistance of both fluids;
11. Calculation of plate number: $N = \frac{\varepsilon \cdot C_{min}(T_1^o - T_2^o)}{K \cdot A_{plate} \cdot \Delta T_m} = \frac{NTU \cdot C_{min}}{K \cdot A_{plate} \cdot \varphi}$ and rounding up the value of N;
12. Comparison of the resulted plate number with the initially chosen value in point 8. When these two values are equal, the real plate number is found; otherwise, the process will be restarted from point 8, giving the calculated N for the chosen value.

The selection of the appropriate criterial equation for determination of the convective heat transfer coefficient from a large number of possibilities is quite a difficult task. We propose to extend the *Neagu et al.* (2014) method as follows:

a) we choose PHE with known geometry and appropriate/similar duty;
b) solving the model with the suggested criterial relations, determining the number of plates with all three convergence methods, and
c) selecting those relations that give close or equal plate number with the real one.

3. Results and discussions

The results of the average thermophysical property calculations

Whole milk density

Figure 1 shows the temperature dependence of the density of whole milk (fat content of 3.9%) based on the relations given in *Table 1a*; the average value is also shown.

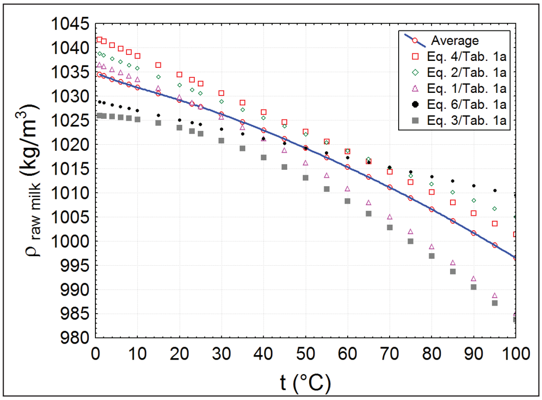

Figure 1. The temperature dependence of the density of whole milk (the curve number represents the equation in *Table 1a*)

The resulted fitted polynomial on the average value is:

$$\rho = 1034.4827 - 0.239955\, t - 0.00119775\, t^2 - 2.016 \cdot 10^{-6}\, t^3,\ \mathrm{kg/m^3},\ \mathrm{kg/m^3} \qquad (5)$$

Whole milk dynamic viscosity

Figure 2 shows the temperature dependence of the dynamic viscosity of whole milk (fat content of 3.9%) based on the relations given in *Table 1b*; the average value is also shown. Correlation 8 (*Ganea & Cojoc*, 2011) was excluded as its results differed substantially from the rest of the values. As can be seen in *Figure 2*, the data are grouped in three distinct domains.

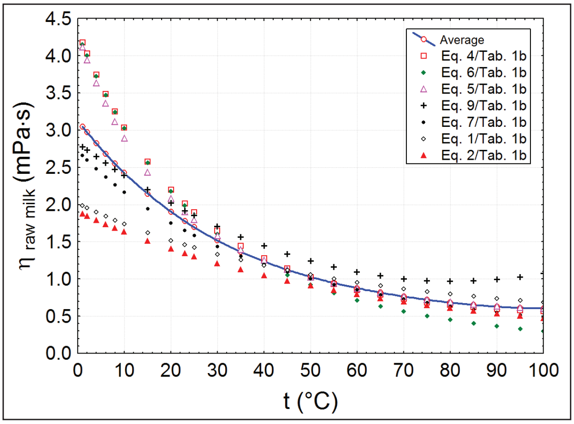

Figure 2. The temperature dependence of the dynamic viscosity of whole milk (the curve number represents the number of equation in *Table 1b*)

The resulted fitted function on the average value is:

$$\eta = 3.14926 \cdot e^{(1.08 \cdot 10^{-4}\, t^2 - 0{,}02765\, t)},\ \mathrm{mPa{\cdot}s} \qquad (6)$$

It should be noted that at any temperature the value of the average viscosity is approximately twice as much as the water viscosity.

Whole-milk-specific heat capacity

Figure 3 shows the temperature dependence of the specific heat capacity of whole milk (fat content 3.9%), based on the relations given in *Table 1c*; the average value is also shown. It is to be mentioned that there exist substantial differences between the predicted values, mainly at lower temperatures, and also in the slope of the fitted line.

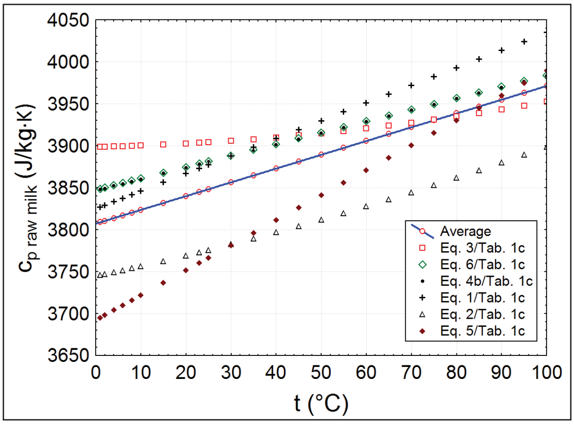

Figure 3. The temperature dependence of the specific heat capacity of whole milk (the curve number represents the number of equation in *Table 1c*)

The resulted fitted polynomial on the average value is:

$$c_p = 3808.7988 - 1.569827\ t,\ \ \mathrm{J/(kg{\cdot}K)} \tag{7}$$

Whole milk thermal conductivity

Figure 4 shows the temperature dependence of the heat capacity of whole milk (fat content 3.9%), based on the relations given in *Table 4*; the average value is also shown. Some relations were omitted since they did not fit into the trend or because they are lacking the data that would have specified the temperature range or fat content. There are substantial differences between the predicted values, mainly at lower temperatures.

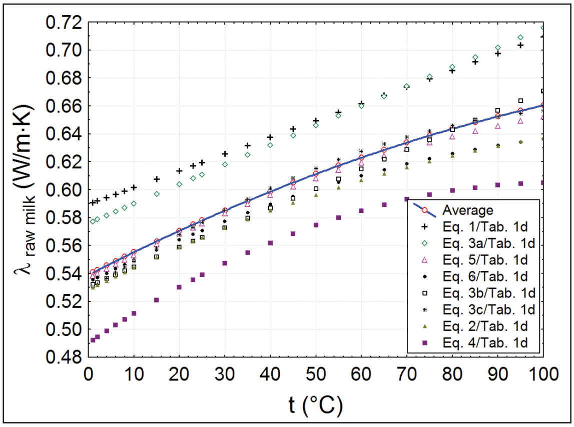

Figure 4. The temperature dependence of the thermal conductivity of whole milk (the curve number represents the number of equation in *Table 1d*)

The resulted fitted function on the average value is:

$$\lambda = 0.539 + 1.6674 \cdot 10^{-3}t - 4.3633 \cdot 10^{-6}t^2 - 1.7715 \cdot 10^{-9}t^3, \text{ W/(m·K)} \tag{8}$$

The selection of the appropriate criterial equations

To select the appropriate criterial equation, we have chosen the Singh and Heldman (2013) case study for PHEs, knowing not only the characteristics of the two fluids but also plate sizes and number. The two chosen heat duties of the PHE ($\dot{Q}$) are shown in *Table 4* and the main geometrical dimensions of the PHE in *Table 5.*

Table 4. The thermal duty of the reference PHE

Fluid	**Mass flow, m_τ, kg/s**	**t^0, °C**	**t, °C**	**t_m, °C**	**$\dot{Q}$, kW**
Water	15 / 1.5	95	47	71	3008 / 300
Apple juice	10 / 1.0	15	87	51	3008 / 300

Table 5. The geometric dimensions of the reference PHE

L, m	**W, m**	**δ, m**	**φ**	**S, m²**	**A_{plate}, m²**	**d_e, m**	**δ, m**	**λ, W/(m·K)**
1.2	0.8	0.004	1.17	0.0032	1.12	0.0068	0.0006	15

The solutions of the model calculation performed with Excel flowsheets are presented in *Table 6.*

Table 6. The results of plate number calculated by several recommended criterial equations

$$Nu = C \cdot Re^m \cdot Pr^n \cdot \left(\frac{\eta}{\eta_{wall}}\right)^p$$

C	**m**	**n**	**p**	**N for 3008 kW**	**N for 300 kW**	**References**
0.4	0.64	0.4	0	50	6	*Singh & Heldman,* 2013
0.273	0.65	0.3/0.4	0	166	19	*Fonyó & Fábry,* 2004
0.352	0.536	0.3	0	266	27	*Maroulis & Saravacos,* 2003
0.023	0.8	0.33	0	No conv.	7100	*Maroulis & Saravacos,* 2003

C	m	n	p	N for 3008 kW	N for 300 kW	References
0.0366	0.8	0.3	0	No conv.	733	*Maroulis & Saravacos*, 2003
0.0188	0.889	0.292	0	No conv.	No conv.	*Gut et al.*, 2004
0.4	0.65	0.4	0	49	6	*Mariott*, 1979
0.374	0.66	0.33	0.15	47	6	*Macovei*, 2001; *Stoica* 1, 2007
0.314	0.666	0.333	0	56	6	*Stoica* 2, 2007
0.157	0.66	0.4	0	252	27	*Okada et al.*, 1972
0.348	0.64	0.33	0.17	63	6	*Kumar*, 1984
0.44	0.5	0.33	0.17	310	26	*Mulley et al.*, 1997/99

Because all three methods (plate number convergence, thermal efficiency, and heat transfer coefficient convergence) led to the same results, the plate convergence method was used for the selection of the criterial equations provided by the literature. Only five of the recommended correlations lead to a value close to reality, resulting 51 (for 3,008 kW) and 6 (for 300 kW) plate numbers. Thus, we continued to work only with the Kumar, Macovei, Stoica 1–2, Mariott, and Singh and Heldman correlations, as could be observed in *Table 6*.

Application of the selected relations to the milk preheater

The plate number for the preheater section of the pasteurizer installation was estimated. The heating was performed from the initial milk storage temperature (4 °C) to the optimal temperature for centrifugal separation (~44 °C) in the single-flow, countercurrent M6-type plate heat exchanger (Alfa Laval). The heat duty of the PHE is shown in *Table 7*, the calculated milk properties in *Table 8*, and the main geometrical dimensions of the M6 PHE in *Table 9*.

Table 7. The thermal duty of the milk preheater

Cold fluid	Mass flow, m_τ, kg/s	t^0, °C	t, °C	t_m, °C	$\dot{Q}$, kW
Whole milk	1.7800	4	44	23	273760
Standardized milk	1.6756	68	26	47	273760

Table 8. Calculated thermophysical properties of milk

Milk type	**t_m, °C**	**ρ kg/m³**	**η mPa·s**	**c_p**	**λ W/(m·K)**	**Pr**
Whole milk	23	1028.32	1.7745	3844.94	0.575	11.85
Standardized milk	47	1020.00	1.057	3890	0.608	6.76

Table 9. The geometric dimension of the modelled PHE, type M6 (Alfa Laval)

L, mm	**W, mm**	**δ, mm**	**φ**	**S, m²**	**A, m²**	**d_e, m**	**δ, m**	**λ_p, W/(m·K)**
920	320	2.5	1.17	0.0007	0.288	0.004273	0.0008	15

The calculation results for the plate number required for preheating are shown in *Table 10*.

Table 10. The numbers of plates determined by the different design methods and the chosen formula for heat exchange coefficient

Name	**Criterial equations**	**K W/(m²K)**	**Calculated plate number (N)**		
			$N_{converg}$	**NTU-e**	**$K_{converg}$**
Kumar	$Nu = 0.348 \cdot Re^{0.640} Pr^{0.333} \left(\frac{\eta}{\eta_{wall}}\right)^{0.15}$	3706	11	11	11
Macovei, Stoica 1	$Nu = 0.374 \cdot Re^{0.666} Pr^{0.400} \left(\frac{\eta}{\eta_{wall}}\right)^{0.17}$	3986–4046	11	11	10
Stoica 2	$Nu = 0{,}314 \cdot Re^{0.666} Pr^{0.3/0.4}$	3680	11	11	11
Mariott	$Nu = 0.4 \cdot Re^{0.65} Pr^{0.4}$	4375	9	9	9
Singh & Heldman	$Nu = 0.4 \cdot Re^{0.64} Pr^{0.4}$	4188	10	10	10

It can be seen that the overall heat transfer coefficient values determined with different equations were situated in the range of K = 3680 – 4375 W/(m²·K), while the required number of plates take values between N = 9 and 11. It can also be seen that the convergence method gave almost the same plate number for each criterial equation. In engineering design, a safety factor is usually recommended, wherefore we propose to use the maximum value of the plate number (N = 11).

4. Conclusions

A key premise for a reliable and realistic computer-aided engineering model solution is the proper selection of the input data; for food engineering purposes, these are mainly the thermophysical properties of the fluids. For modelling purposes, using continuous functions are more adequate than tabular data. Therefore, mainly polynomial or exponential functions are used for the determination of the value of temperature-dependent thermophysical property of the two exchanger fluids. The proposed data estimation method could be used for both tabular and correlation-based data selection and processing. By averaging the literature data from multiple sources describing the thermophysical properties of milk, equations were fitted, enabling the estimation of a property of adequate accuracy within a given range of temperature, and even beyond, using prudent extrapolation. In order to estimate the plate numbers of a PHE, in addition to the properties, it is necessary to know the criterial equations established between the corresponding dimensionless numbers. When we do not have a relation corresponding to the geometry of the plate (this is the case for most design tasks), it is necessary to select the appropriate one from the many relations recommended by the literature. For this purpose, we propose a useful methodology – somehow with reverse engineering philosophy – by recalculating the plate numbers of a known heat exchanger with the available relations. Based on the obtained results, those criterial equations are worth choosing which give close results to the real plate numbers. Using the selected criterial equation(s), the plate number required to perform the given thermal duty can be determined with good accuracy, using either the plate number convergence ($N_{converg}$), the overall heat transfer convergence ($K_{converg}$), or the thermal efficiency (NTU-ε) for resolving the PHE model. In future PHE design, we recommend the presented method for criterial equation selection.

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Appendices

Appendix 1. Criterial equations suitable for estimating heat transfer coefficient for PHEs

No.	Equations	References
1.	$Nu = 0.273 \cdot Re^{0.65} Pr^{m} \cdot \left(\frac{\delta}{L}\right)^{0.35}$ m= 0.3 ↓ / 0.4 ↑	*Fonyó & Fábry*, 2004
2.	$Nu = 0.4 \cdot Re^{0.64} Pr^{0.4}$	*Singh & Heldman*, 2013
3.	$Nu = a \cdot Re^{m} Pr^{1/3}$ $Re > 5 \;\; a = 0.352;\; m = 0.539$	Maroulis & Saravacos, 2003
4.	$Nu = 0.023 \cdot Re^{0.8} Pr^{1/3}$	
5.	$Nu = 0.664 \cdot Re^{0.5} Pr^{1/3}$; Laminar	
6.	$Nu = 0.0366 \cdot Re^{0.8} Pr^{1/3}$; Turbulent	
7.	$Nu = 0.0188 \cdot Re^{0.889} Pr^{0.292}$ $\quad 10 < Re < 1000$	*Gut et al.*, 2004
8.	$Nu = 0.273 \cdot Pr^{1/3}$ $\quad 10 < Re < 1000$	
9.	$Nu = 0.273 \cdot Re^{0.65} Pr^{0.4} (W/L)^{0.36}$	*Kreith et al.*, 1999
10.	$Nu = 0.0169 \cdot Re^{0.897} Pr^{0.3} (W/L)^{0.36}$	
11.	$Nu = C \cdot Re^{x} Pr^{y} \left(\frac{\eta}{\eta_{wall}}\right)^{z}$ $Laminar: Re < 400 \;\; Turbulent\ Re > 400$ $C = 0.15 \ldots 0.4; x = 0.65 \ldots 0.85; y = 0.3 \ldots 0.45;$ $z = 0.05 \ldots 0.2$	*Mariott*, 1971
12.	$Nu = 0.0645 \cdot Re^{0.78} Pr^{0.46}$	*Macovei*, 2001
13.	$Nu = 0.374 \cdot Re^{0.666} Pr^{0.333} \cdot \left(\frac{\eta}{\eta_{wall}}\right)^{0.15} \;\; Re > 400$	*Macovei*, 2001 *Stoica et al.*, 2007
14.	$Nu = 0.314 \cdot Re^{0.666} Pr^{y} \quad y = 0.3 \;\downarrow and\;\; y = 0.4 \;\uparrow$	
15.	$Nu = 0.718 \cdot Re^{0.349} Pr^{0.33};\; \beta = 30°$	*Mota et al.*, 2015
16.	$Nu = 0.157 \cdot Re^{0.666} Pr^{0.4};\;\; \beta = 30°$	*Okada et al.*, 1972
17.	$Nu = 0.249 \cdot Re^{0.64} Pr^{0.4};\;\; \beta = 45°$	

No.	Equations	References
18.	$Nu = 0.327 \cdot Re^{0.65} Pr^{0.4};\ \beta = 60°$	*Okada et al.*, 1972
19.	$Nu = 0.478 \cdot Re^{0.62} Pr^{0.4};\ \beta = 75°$	
20.	$Nu = 1.89 \cdot Re^{0.46} Pr^{0.5};\ \beta = 60°$ and $20 < Re < 150$	*Focke et al.*, 1985
21.	$Nu = 0.57 \cdot Re^{0.7} Pr^{0.5};\ \beta = 60°$ and $150 < Re < 600$	
22.	$Nu = 1.12 \cdot Re^{0.6} Pr^{0.5};\ \beta = 60°$ and $600 < Re < 16000$	
23.	$Nu = 1.67 \cdot Re^{0.44} Pr^{0.5};\ \beta = 45°$ and $45 < Re < 300$	
24.	$Nu = 0.405 \cdot Re^{0.7} \cdot Pr^{0.5};\ \beta = 45°$ and $300 < Re < 2000$	
25.	$Nu = 0.84 \cdot Re^{0.6} Pr^{0.5};\ \beta = 45°$and $2000 < Re < 20000$	
26.	$Nu = 0.77 \cdot Re^{0.54} Pr^{0.5};\ \beta = 30°$ and $120 < Re < 1000$	
27.	$Nu = 0.44 \cdot Re^{0.64} Pr^{0.5}; \beta = 30°$ and $1000 < Re < 42000$	
28.	$Nu = 0.72 \cdot Re^{0.59} Pr^{0.4} \phi^{0.41} \left(\frac{\beta}{30}\right)^{0.66};$ $30° < \beta < 80°$ and $1000 < Re < 4000$	*Chisholm et al.*, 1999
29.	$Nu = 0.471 \cdot Re^{0.5} Pr^{0.33} \left(\frac{\eta}{\eta_{wall}}\right)^{0.14};$ $\beta = 30° \ldots 60°$ and $20 < Re < 400$	*Muley et al.*, 1997
30.	$Nu = 0.1 \cdot Re^{0.76} Pr^{0.33} \left(\frac{\eta}{\eta_{wall}}\right)^{0.14};\ \beta = 30° \ldots 60°$ and $Re > 1000$	
31.	$Nu = 1.6774 \cdot \left(\frac{d_e}{L}\right)^{0.333} \left(\frac{\beta}{30°}\right)^{0.38} Re^{0.5} Pr^{0.33} \left(\frac{\eta}{\eta_{wall}}\right)^{0.14};$ $\beta = 30° \ldots 60°$ and $30 \leq Re < 400$	
32.	$Nu = 0.278 \cdot \varphi^{0.317} Re^{0.683} Pr^{0.33} \left(\frac{\eta}{\eta_{wall}}\right)^{0.17};$ $\beta = 45°/90°$ and $400 < \frac{Re}{\phi} < 10000$	*Heavner*, 1993
33.	$Nu = 0.308 \cdot \varphi^{0.333} Re^{0.667} Pr^{0.33} \left(\frac{\eta}{\eta_{wall}}\right)^{0.17};$ $\beta = 23°/90°$ and $400 < \frac{Re}{\phi} < 10000$	
34.	$Nu = 0.195 \cdot \varphi^{0.308} Re^{0.692} Pr^{0.33} \left(\frac{\eta}{\eta_{wall}}\right)^{0.17};$ $\beta = 45°/45°$ and $400 < \frac{Re}{\phi} < 10000$	
35.	$Nu = 0.118 \cdot \varphi^{0.280} Re^{0.720} Pr^{0.33} \left(\frac{\eta}{\eta_{wall}}\right)^{0.17};$ $\beta = 23°/45°$ and $400 < \frac{Re}{\phi} < 10000$	

No.	Equations	References
36.	$Nu = 0.089 \cdot \varphi^{0.282} Re^{0.718} Pr^{0.33} \left(\frac{\eta}{\eta_{wall}}\right)^{0.17}$; $\beta = 23°/23°$ and $400 < \frac{Re}{\phi} < 10000$	*Heavner*, 1993
37.	$Nu = 0.023 \cdot Re^{0.8} Pr^{0.33} \left(\frac{\eta}{\eta_{wall}}\right)^{0.14}$; $\beta = 30°/30° - 30°/45° \ldots 60°/60°$ and $Re > 4000$	*Wang et al.*, 2007
38.	$Nu = 0.348 \cdot Re^{0.64} Pr^{0.4} \left(\frac{\eta}{\eta_{wall}}\right)^{0.17}$; $\beta = 30\,°$	Kumar equation *Neagu et al.*, 2014
39.	$Nu = 0.44 \cdot \left(\frac{\beta}{30}\right)^{0.38} Re^{0.5} Pr^{0.33} \left(\frac{\eta}{\eta_{wall}}\right)^{0.17}$	Mulley equation *Kakaç & Liu*, 2002
40.	$Nu = 0.329 \cdot Re^{0.529} Pr^{0.33} \left(\frac{\eta}{\eta_{wall}}\right)^{0.17}$; $\beta = 30\,°$	Bond equation *Gulenoglu et al.*, 2014
41.	$Nu = 0.45 \cdot \left(RePr\frac{d_h}{L_v}\right)^{0.333} \left(\frac{\eta}{\eta_{wall}}\right)^{0.17}$; $\beta = 30\,°$	Buonopane–Troupe equation, *Thulukkanam*, 2013
42.	$Nu = 0.263 \cdot Re^{0.65} Pr^{0.4}$	*Buonopane et al.*, 1963
43.	$Nu = C \cdot Re^{m} Pr^{n} \Gamma$ C, Γ and m, n are presented in *Appendix 2*.	*Muley*, 1999

Appendix 2. The C coefficient and m, n exponents of the proposed relation (*Mulley*, 1999), as a function of the angle of inclination of the folds

Angle	**C**	**m**	**n**	**Γ**	**Re**
V shape 30 °	0.718	0.349	1/3	$\left(\frac{\eta}{\eta_{wall}}\right)^{0.17}$	*<10*
	0.348	0.64	1/3		*10… 100*
	0.329	0.529	1/3		
	$0.44\left(\frac{6\beta}{\pi}\right)^{0.36}$	0.5	1/3		
V shape 45 °	0.718	0.349	1/3		*< 10*
	0.4	0.598	1/3		*10…100*
	0.3	0.663	1/3		*> 100*

Angle	**C**	**m**	**n**	**Γ**	**Re**
V shape 50 °	0.63	0.333	1/3	$\left(\frac{\eta}{\eta_{wall}}\right)^{0.17}$	*< 20*
	0.291	0.591	1/3		*20…300*
	0.13	0.732	1/3		*> 300*
V shape 60 °	0.562	0.326	1/3		*< 20*
	0.306	0.529	1/3		*20…400*
	0.108	0.703	1/3		*> 400*
V shape 65 °	0.562	0.326	1/3		*< 20*
	0.331	0.503	1/3		*20…500*
	0.087	0.718	1/3		*> 500*