CFD based rating problem calculation of electrical LPG vapourizer

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Abstract

In the present article operating characteristics of LPG (liquified petroleum gas) revaporizer are analysed. At the beginning description of electrical revaporizer as well as the problem definition are presented. 2D numerical model of revaporizer is introduced and main assumptions for that simplification are explained. Governing equations of fluid flow in the region of natural convection and porous region of computational domain are given. Boundary conditions are prescribed on the basis of heat transfer empirical correlations for single- and two-phase flow in helically coiled tubes and correlations for external flow around revaporizer shell. Finally, results of CFD analysis and main conclusions are presented. Computational results show that revaporizer operates within prescribed temperature range for selected combination of process parameters.

1 Introduction

Liquified petroleum gas is used as commercial name for propane (C\textsubscript{3}H\textsubscript{8}), butane (C\textsubscript{4}H\textsubscript{10}), and arbitrarily composed mixtures of these hydrocarbonates. At lower gauge pressures and surroundings temperature LPG has liquid aggregate state. This is an important characteristic of LPG used for its economical transport. Before LPG is used in burner, it must be once again transformed to gas aggregate state. At small consumption rate a heat from surroundings commonly satisfies revaporization purposes. Large consumers require promoted revaporisation and because of that LPG revaporizers are introduced in gas networks. They are two-phase heat exchangers, which use heat energy from external sources to promote evaporation of LPG. Present article deals with electrical LPG revaporizer with secondary liquid for heat transfer.

Revaporizer consists of cylindrical shell into which tube bundle and electrical resistance heater are inserted (figure 1). Tube bundle is a double once-through helically coiled tube with connecting sections. Electrical coverage heater is inserted into the central part of the revaporizer vessel. Inlet and outlet connections, control equipment, measurement and auxiliary fittings are installed.
on the revaporizer cover. Electrical heater supplies heat energy and secondary liquid in revaporizer shell (mineral oil) is warmed up to working temperature. Due to this, natural convection occurs and heat is transferred to tube bundle. Within tube bundle convective flow boiling and superheating of gas LPG phase take place. Thermostats serve as control components for the electromagnetic valve (inlet control of LPG) and electric heater (switch on-switch off function) and are placed on the revaporizer cover.

In the present work, an industrial revaporizer was analysed. It operates at different process parameters. Process parameters affecting operational characteristics of revaporizer are (1) composition of LPG ($\xi_{C_3H_8}$), (2) surroundings temperature ($T_{sur}$), (3) mass flow of LPG ($m_{LPG}$), (4) air flow around the shell ($v_w$), (5) secondary liquid type, and (6) its liquid level height in revaporizer vessel. Any combination of process parameters defines one working point of revaporizer. Typical combination of these parameters was selected and CFD analysis of revaporizer and there conditions was performed. Selected parameters are presented in Table 1.

![Revaporizer Interior and Axisymmetrical Section](image)

**Figure 1. Interior and axisymmetrical section of revaporizer**
(1-electrical heater, 2-tube bundle, 3-liquid phase inlet, 4-gas phase outlet)

<table>
<thead>
<tr>
<th>$T_{sur}$ [$^\circ$C]</th>
<th>$\xi_{C_3H_8}$ [%]</th>
<th>$m_{LPG}$ [kg/h]</th>
<th>$v_w$ [m/s]</th>
<th>Heat transfer liquid</th>
<th>$H_d$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 20.0</td>
<td>0.6</td>
<td>1.0 · $m_{LPG, opt}$</td>
<td>10.0</td>
<td>mineral oil</td>
<td>$H_{sl,max}$</td>
</tr>
</tbody>
</table>

**Table 1. Selected process parameters for CFD analysis**
2 Numerical model

3D numerical model of the chosen revaporizer geometry would be too complex for CFD analysis on a workstation type of computer. Due to this fact we introduced quasiaxisymmetrical model of revaporizer. Some assumptions have to be done in order to justify this simplification. Processes of convective flow boiling and superheating of LPG are extended along large portions of tube bundle. On that basis, physics of mentioned processes was reduced from a whole helically tube turn to one corresponding circular section in axisymmetrical plane of revaporizer. Also electrical heater is compactly formed and this fact was used to introduce porous plane region in the central part of revaporizer. This was done by selecting suitable porosity and permeability values based on geometry of the electrical heater. The resulting quasiaxisymmetrical section of revaporizer is presented in Figure 2.

3 Governing equations

Numerical calculation of flow and temperature fields was performed in the region of natural convection of secondary liquid in the revaporizer shell and in the region of porous heater. Governing equations, describing the physics of the problem, can be written separately for natural convection in pure fluid and in porous region.

3.1 Natural convection

![Figure 2. Quasiaxisymmetrical model of revaporizer (1-natural convection region, 2-porous heater region)](image)

General form of continuity equation [1] is written as
where $\rho$ is the fluid density and $u_i$ is the velocity vector. Momentum equation with Boussinesq's approximation, where the temperature influence on fluid mass density is considered only within the body force term, is written as

$$\frac{\partial \rho}{\partial t} + (\rho u_i)_i = 0, \quad (1)$$

In equation (2), $\rho_0$ represents the fluid density at reference temperature $T_0$, $p$ is thermodynamic pressure, $\mu$ is the dynamic viscosity and $g_i$ is the gravity vector. Correlation $(\rho - \rho_0)/\rho_0 = -\beta_T(T - T_0)$ represents a normalized density temperature variation function, where $\beta_T$ is thermal volume expansion coefficient. Energy equation with temperature as independent variable is

$$\rho c_p \left( \frac{\partial T}{\partial t} + u_i T_i \right) = (\lambda T)_i + I, \quad (3)$$

where $c_p$ is specific heat at constant pressure, $T$ stands for temperature, $\lambda$ is the heat conductivity and $I$ is the heat source.

### 3.2 Porous region

Continuity equation is presented with expression (1). Momentum equation for porous region is

$$\frac{\rho \cdot \partial u_i}{\phi \cdot \partial t} + \left( \frac{\rho \sigma}{\sqrt{k_i}} \|u_i\| + \frac{\mu}{\kappa_i} \right) u_i = -p_i + \left[ \mu(u_{i,j} + u_{j,i}) \right]_j + \rho g_i, \quad (4)$$

where $\phi$ is the porosity, $\sigma$ is the inertia coefficient, $k_i$ is the permeability of porous matter, $\|u_i\|$ is the magnitude of the velocity and $\mu$ is an effective dynamics viscosity. Energy equation is written as

$$\left( \rho c_p \right)_e \frac{\partial T}{\partial t} + \rho c_p u_j T_j = (\lambda_e T)_j + I, \quad (5)$$

where subscript $e$ indicates an effective property whose value needs to be prescribed on the basis of an averaged properties of liquid and solid phase. These
properties are defined by next expressions: \((\rho_c p)_e = \phi \rho_c p + (1 - \phi)(\rho_c p)_s\), 
\(\lambda_e = \phi \lambda + (1 - \phi)\lambda_s\) in \((\rho a)_e = \phi \rho a\). Here, subscript \(s\) refers to solid matrix properties. Properties without subscripts are those of the liquid phase. Equation system presented above is sometimes referred to as the Forchheimer-Brinkmanov model for porous flow.

4 Boundary conditions

General form of velocity boundary condition is written as

\[ u_i = u_i(l, t), \quad (6) \]

where \(l\) is the coordinate distance along appropriate boundary. Zero velocity boundary condition is prescribed along all solid boundaries. On the symmetry axis of revaporizer normal velocity has to be zero and in symmetry axis direction free velocity boundary condition is set. Mixed (Cauchy) boundary conditions are prescribed along all boundaries of computational domain. These boundaries are bottom, shell, and cover of revaporizer and circular sections of helically tube where convective boiling and superheating of LPG occur. General form of mixed boundary condition is presented by expression

\[ \dot{q} = \alpha(T - T_{ref}), \quad (7) \]

where \(\dot{q}\) is the heat flux, \(\alpha\) is convective heat transfer coefficient and \(T_{ref}\) is a reference temperature (surrounding temperature). Heat conduction through solid walls of computation region was also taken into consideration. Thus, next expression for modified heat transfer coefficient was achieved

\[ \alpha' = 1/(R + 1/\alpha), \quad (8) \]

where \(R\) represents heat conduction resistance. Neumann boundary condition (constant heat flux)

\[ \dot{q} = konst., \quad (9) \]

were prescribed along boundaries of porous heater.

4.1 Temperature boundary conditions

Temperature boundary conditions in the region of convective boiling of binary mixture of propane and butane are written as

\[ T_{ref} = T_{bub} + (n_{cb} - 1)\Delta T_{cb}, \quad (11) \]
Convective boiling, defined by expression

\[ \Delta T_{cb} = \left( T_{dew} - T_{lab} \right) / n_{cb}. \]  

where \( T_{lab} \) is the bubble point temperature of propane-butane mixture, \( n_{cb} \) is the tube turns number in the region of convective boiling and \( \Delta T_{cb} \) is temperature difference between adjacent turns of helically coiled tube in the region of convective boiling, defined by expression

\[ \Delta T_{cb} = \left( T_{dew} - T_{lab} \right) / n_{cb}. \]  

4.2 Convective boiling in helically coiled tube

In the open literature there are no systematically settled expressions for convective boiling heat transfer coefficients in helically coiled tubes. The same statement holds for convective flow boiling data for propane-butane mixtures. Convective boiling correlation by Kandlikar [2] for the most interesting mixtures explored in the past was used in our analysis. Author extended well-known correlation for pool boiling of binary mixtures and connected it with his own correlaion for convective flow boiling of ordinary liquid. On the basis of volatility and boiling number the region of moderate suppression of nucleate boiling due to influence of diffusion effects was selected. Two-phase heat transfer coefficient in this region is defined by the following expression

\[ \alpha_{TP,\text{CBD}} = \alpha_{lo} (1 - x)^{0.8} \cdot \left[ 1.136 \cdot Co^{-0.9} \cdot f_2(Fr_{lo}) + 667.2 \cdot Bo^{0.7} \cdot F_{fl,m} \right]. \]  

where \( T_{out} \) is outlet temperature of propane-butane vapour phase.

\[ T_{ref} = T_{dew} + \left( n_{sup} - 1 \right) \Delta T_{sup}, \]  

where \( n_{sup} \) represents tube turns number in the region of superheating of propane-butane mixture, \( \Delta T_{sup} \) is temperature difference between adjacent tube turns in the superheating region, defined by expression

\[ \Delta T_{sup} = \left( T_{out} - T_{dew} \right) / n_{sup}. \]  

where \( T_{out} \) is outlet temperature of propane-butane vapour phase.
For $Fr > 0.4$ at horizontal tubes and for vertical tubes with $Fr > 0.4$. For $Fr \leq 0.4$ at horizontal tubes value of $f(25Fr)^{0.3}$. $Fr$ number with all flow as liquid is defined as

$$Fr = \frac{G^2}{\rho_l g d_{in}},$$

The boiling number is defined as

$$Bo = \frac{\dot{q}}{G h_v},$$

where $G$ is the mass flux, $h_v$ is the evaporation enthalpy and $d_{in}$ is the inside tube diameter.

### 4.3 Single-phase flow in helically coiled tubes

In the helically coiled tubes secondary movement of fluid particles transversely on main axial fluid stream occurs [6]. Fluid flow consists of pairs of helical spiral vortices. Differences of thermo-hydraulic characteristics between the straight and helically coiled tubes are consequence of this phenomenon. Heat transfer coefficient in the region of single-phase flow in helically coiled tubes is defined by Gnielinski [3] correlation and written as

$$Nu = \frac{\xi/8 \cdot Re \cdot Pr}{1 + 12.7 \sqrt{\xi/8 (Pr^{2/3} - 1)}},$$

where $\xi$ is friction factor defined as

$$\xi = \left[ \frac{0.3164}{Re^{0.25}} + 0.03 \left( \frac{d_{m}}{D_{mc}} \right)^{0.5} \right],$$

where $D_{mc}$ is the mean diameter of the helically coiled tube.

### 5 Results
HIDAP 8.5 program package [1] was used to solve governing equations of fluid flow. The program has unstructured grid capability. Numerical results were tested with regard to computational grid density. Computational grid that gave satisfactory results had 14,900 finite elements in the region of natural convection and 1900 elements in the region of porous heater. Velocities in both regions are low and flow is laminar. A special iterating procedure has to be undertaken in order to achieve convergence of mass and heat flows in the revaporizer. Boundary conditions are changed step by step in calculating procedure until partial and integral heat balances of revaporizer are satisfied.

Figure 3: Temperature field in the region of thermostat probes placing (final calculating state)

Heat transfer coefficients and reference temperatures (boundary conditions) within tube turns, in the first calculating step, are prescribed on the basis of assumption of uniform heat flux distribution along tube bundle. Heat transfer coefficients and temperatures in the last calculation step, when nonuniform distribution of heat flux along tube bundle was taken into consideration, shown substantial differences as for initial assumption. The results of computations show that convective flow boiling occurs within 21 tube turns. Mass vapour
quality at the onset of tube wall dryout is $x_{\text{ini}} = 0.41$. Number of tube turns with total wetting of tube wall is 9. Inside 12 tube turns partial dryout of tube wall is present. From that point superheating of vapour phase occurs.

Values of temperature in points where control thermostat probes are placed must lie in the prescribed working ranges. Operating area of control thermostats is from 65 to 85 °C. Computed temperature in the point where electromagnetic valve thermostat probe is placed was 76 °C. This value corresponds to process parameter combination given in Table 1. In Figure 3 temperature field in region where control thermostat probes are placed is presented.

6 Conclusion

The presented paper deals with numerical simulation of heat and flow conditions inside the electrical LPG revaporizer. In the region of secondary liquid flow CFD analysis was performed, and inside the tubes empirical correlations were used in order to account for the phase change phenomena during convective boiling of LPG. Converged results are achieved for chosen combination of process parameters. Results are valid for moderate operating condition. Temperatures in point where thermostat probes are placed are within prescribed values. Kandlikar correlation for convective boiling of binary mixtures in straight tubes may be used for boiling in helically coiled tubes because of low values of heat fluxes, mass fluxes and low values of centrifugal forces that occur in helically tube bundle of revaporizer. This assumption obviously has not had influence on final results.

References