Non-stationary heat transfer from spherical vessels under free convection. Investigation of liquid petroleum products storage

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Abstract. A study of the non-stationary heat transfer from spherical vessels under free convection was performed in the laboratory. From this study, a set of mathematical correlations between *Nusselt* and *Grashof* numbers resulted, with the practical goal of calculating the heat transfer coefficient in industrial applications of petroleum products storage, for the estimation of insulation necessities. It was found that the linearity of Nusselt (*Nu*) correlated with Grashof (*Gr*) is valid for values of Nu<30. Over this value, the Gr depends strongly on the size of the body, *Gr* being proportional to the diameters ratio raised at power 2.5.

Keywords: heat transfer, free convection, petroleum storage

1. Introduction

Non stationary heat exchange systems occur in industry, especially in transport and storage of liquid products, specifically for liquids in pipes or tanks. Tanks and pipes can be insulated or no, they can be placed in the ground or in the air. The problem arises for the temperature variation of the environment, causing boiling in some cases, solidification in other cases or asking for the compensation of the heat transferred to the medium. The chemical engineers developed calculation methods for this heat transfer regime for specific cryogenic systems [1,2] where variations of the environmental temperature can lead to boiling of the stored liquids (Helium, Freon) causing waste of the product. Also, there were calculated specific cases of pipes [3,4] or equipment [5, 6], for the estimation of the heat flux transferred.

The non stationary heat transfer from pipes and storage vessels is common in the petroleum processing industry. The problem is very important for the liquids stored in spheres. The study of these systems can be done in laboratory, the aim being the development of a mathematical model for describing the process and calculate the heat transfer between the liquid and the environment.

2. Theoretical aspects

In case of free convection around spherical bodies, Nusselt (*Nu*) and Grashof (*Gr*) numbers are proportional [6], *Nu* increasing with increasing value of *Gr* (**Eq.1**):

$$\frac{Nu^3}{(1-2/Nu)^6} = C_1 Gr \qquad \textbf{(1)}$$

where:

$$Nu = \frac{2r\alpha}{\lambda} \qquad \textbf{(2)}$$

and:

$$Gr = \frac{8r^3 g\beta\Delta t}{\upsilon^2} \qquad \textbf{(3)}$$

In **Eq. 2** and **3**, α is the overall heat transfer coefficient, r is the radius of the sphere, g is the gravitational constant, υ, β and λ are the kinematic viscosity, the volumetric expansion coefficient and the thermal conductivity of the environmental fluid and Δt is the temperature difference between the body and the environment.

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The overall transfer coefficient α in case of a sphere is defined by **Eq.4**:

$$q = \alpha\pi \cdot r^2 \Delta t \qquad \textbf{(4)}$$

where q is the thermal flux transferred (W).

So, by determining the thermal flux, one can calculate further the coefficient α. The thermal flux can be calculated with the formula (**Eq.5**):

$$q = \frac{Q}{\tau} = \frac{m \cdot c_p \cdot \Delta t}{\tau} \qquad \textbf{(5)}$$

where Q is the sphere liquid heat exchanged with the environment (J), m and c_p are the mass and the liquid specific heat and τ is the time in wich Q was exchanged. Form (5) is valid in case of a stationary state but the unsteady heat exchange can be considered as a succession of stationary states. So, from Eq.2-5, *Nu* and *Gr* numbers can be calculated for a succession of experimental data and then they can be correlated with Eq.1 to find the value of the constant C_1. If needed, another equation can be found between *Nu* and *Gr*.

The involved physical properties are: density, viscosity, specific heat and thermal conductivity. These properties are variable with temperature.

Data for the variation with temperature of water and air properties are well known [8]. For petroleum fractions and pure hydrocarbons, the properties are calculated with empirical relationships [9]. For the density and the specific heat (which intervenes in calculation), these relationships are (**Eq.6** and **7**):

$$\rho = 10^3 \cdot d_4^{20} \left[1 - \frac{t-20}{2290 - 6340 \cdot d_4^{20} + 5965 \left(d_4^{20}\right)^2} \right] \quad [\mathrm{kg/m^3}] \qquad (6)$$

$$c_p = \left[\left(2{,}964 - 1{,}332 d_{15}^{15}\right) + \left(0{,}006148 - 0{,}002308 d_{15}^{15}\right) \cdot t \right] \cdot \left(0{,}0538K + 0{,}3544\right) \quad [\mathrm{kJ/kg \cdot {}^0C}] \qquad (7)$$

For pure hydrocarbons, the variation of density and specific heat can be calculated with the following relationships (**Eq. 8** and **9**) [9]:

$$\rho = a + \sqrt{b - c \cdot t} \quad [\mathrm{kg/m^3}] \qquad (8)$$

where a, b, c, are coefficients for toluene in the range 0-300 ^{0}C are: a = 337.919, b = 299 597.7, c = 936.793

and:

$$c_p = A + B \cdot t + C \cdot t^2 \quad [\mathrm{J/kg \cdot {}^0C}] \qquad (9)$$

where: $A \cdot 10^{-2}$ = 14.553, B = -0.066365, $C \cdot 10^2$ = 0.38309, for the temperature range 0-200 ^{0}C.

3. Experimental

The temperature variation is measured for different nature cooling liquids, stored in spherical vessels. Three glass spherical flasks are suspended in the air, in the absence of air eddies and heat sources. Balloons are of different size with external diameters ranging from 84 mm to 135 mm. The inner diameter was determined by measuring the volume of liquid needed to fill the balloon. The flask neck was sealed with a rubber stopper through which a thermometer was placed it the middle of the liquid, measuring the temperature with 0.1 ^{0}C precision.

The cooling started temperature was t = 80 ^{0}C, being limited by the proximity of boiling point for toluene (110 ^{0}C). During the study, room temperature was 23 ^{0}C. The temperature variation was monitored when the same liquid is cooled in balloons of different size. The residence time was between 1 and 2.25 hours, readings being made at intervals of 0.25 hours.

4. Results and Discussions

The experimental data for the cooling of liquids in spherical vessels are presented in **Tables 1-3.**

The values of *Nu* and *Gr* criteria were calculated in each case in order to characterize the natural convection in the air around the vessels. The correlation of *Nu* and *Gr* was linear as described by Eq.1 only for *Nu* up to 30. In this case C_1=0.0148 with 0.0028. standard deviation

For higher values of *Nu,* the correlation is not linear and strongly depends on the size (diameter) of the body. That's why the experimental data were separated for different diameters of the vessel, whatever was the size of the vessel and three correlation curves were obtained, as seen in **Fig.1.**

Table 1. Experimental data for water cooling in spherical vessels

Balloon number	1	2	3
Internal diameter D_i, [mm]	83.1	107.6	133.4
External diameter D_e, [mm]	84.2	109.0	135.2
Room temperature, t_m, [^{0}C]	23	23	23
Residence time, τ [h]	Liquid temperature, t [^{0}C]		
0	80	80	80
0.25	59	62	69
0.50	48	55	61.5
0.75	45	49	55
1	37	44	50
1.25	33	40	46
1.50	31	37	43
1.75	-	34	39.5
2	-	33	38
2.25	-	32	36.5

Table 2. Experimental data for toluene cooling in spherical vessels

Balloon number	1	2	3
Internal diameter D_i, [mm]	83.1	107.6	133.4
External diameter D_e, [mm]	84.2	109.0	135.2
Room temperature t_m, [^{0}C]	23	23	23
Residence time τ [h]	Liquid temperature t [^{0}C]		
0	80	80	80
0.25	49	57	57
0.50	38	45	46
0.75	32	37	39
1	29	32	34
1.25	26	29	31
1.50	-	26	29.8
1.75	-	-	27.5
2	-	-	26.5
2.25	-	-	25.5

Table 3. Experimental data for Diesel cooling in spherical vessels

Balloon number	1	2	3
Internal diameter D_i, [mm]	83.1	107.6	133.4
External diameter D_e, [mm]	84.2	109.0	135.2
Room temperature t_m, [^{0}C]	23	23	23
Residence time τ [h]	Liquid temperature t, [^{0}C]		
0	80	80	80
0.25	49	58	60
0.50	36	46	48.5
0.75	34	35	41.5
1	29.8	32	36
1.25	28.2	31	32.5
1.50	26.2	29	29
1.75	25.6	25	27
2	-	24	25
2.25	-	-	24.5

The **Eq. 10-12** describe the correlation between *Nu* and *Gr* numbers for *Nu>30*:

For D_1=84 mm:

$$Gr = 1 \cdot 10^6 \ln Nu - 2 \cdot 10^6 \quad \textbf{(10)}$$

For D_2=109 mm:

$$Gr = 3 \cdot 10^6 \ln Nu - 9 \cdot 10^6 \quad \textbf{(11)}$$

For D_3=135 mm:

$$Gr = 6 \cdot 10^6 \ln Nu - 2 \cdot 10^7 \quad \textbf{(12)}$$

From Eq.10-12, it was noticed that at the same value of *Nu*, the value of *Gr* is proportional to the diameters ratio raised at power 2.5, this indicating that *Gr* depends strongly on the size of the body (**Eq. 13-14**):

$$Gr \sim \left(\frac{D_2}{D_1}\right)^{2.5} \qquad (13)$$

$$Gr_2 = Gr_1 \cdot \left(\frac{D_2}{D_1}\right)^{2.5} \qquad (14)$$

For bigger bodies, the *Gr* number can be calculated with Eq.14.

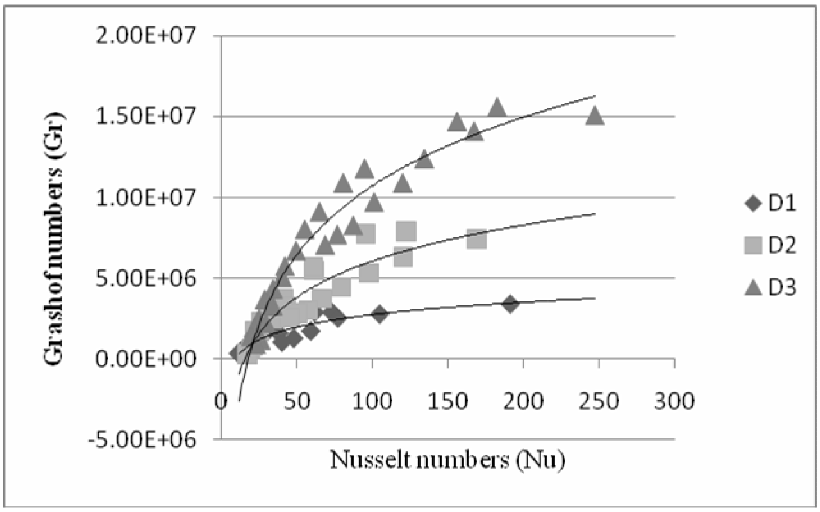

Fig.1. The correlation of *Nu* and *Gr* criteria for the natural convection process around the spherical bodies cooling in the air

4. Conclusions

The present study aimed to verify older correlations concerning the natural convection around hot bodies and eventually to find new ones. It was found that the linearity of Nusselt (*Nu*) correlated with Grashof (*Gr*) is valid for values of Nu<30. Over this value, the Gr depends strongly on the size of the body. The nature of the fluid cooling doesn't affect the convection in the air.

The correlations found in this study can be used for indirect calculation of the transfer coefficient for the heat transfer from hot spherical bodies to the environment and subsequently to calculate the insulation needed in each case.

5. References

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[1]. V.A.Grigoriev, Yu.M.Pavlov and I.V. Yakovlev, Criogenics, **25**, 81-86 (1985).

[2]. V.N.Zhukov, Yu.A. Kuzma Kichta, and A.M. Agal'tsov., Heat transfer research, **4**, 479-491 (2010).

[3]. E.E. Prokhach, Inzhenerno-Fizicheskii Journal, **17**(6), 1005-1009 (1969).

[4]. P.M.Kolesnikov and V.I.Bubnovich, Int.J.Heat Mass Transfer, **31**(6), 1146-1156 (1988)

[5]. S.V. Shikilev, S.A. Ermakov and I.F. Reshetnikov, Physicochemical studies of systems and processes, **81**(9), 1508-1511 (2008)

[6]. D. L. Movileanu, The study of free convection in liquids in non-stationary regime (in Romanian). Ph.D. Thesis, Ploieşti, 2002

[7]. H. Kramers, Physica **XII**(2-3), 61-80 (1946).

[8]. K. Raznjevic, Thermodynamic tables and diagrams (In Romanian), Editura Tehnică, Bucureşti, 1978

[9].V. Şomoghi, D. Dobrinescu, C. Patrascu, M. Patrascu and V. Ioan, Physical properties for calculations in thermodynamics and fluid flow (in Romanian), U.P.G., Ploieşti, 1997.