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# NEW EMPIRICAL CORRELATIONS FOR PREDICTING THE THERMAL CONDUCTIVITY AND VISCOSITY OF NANOFUIDS $Al_2O_3$ /WATER

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**Abstract.** *This work concerns the development of empirical correlations to predict the thermal conductivity and dynamic viscosity of nanofluids composed of  $Al_2O_3$ /water by the theory of Vaschy-Buckingham. The database used in this work has 264 results for the thermal conductivity and 258 for the viscosity, with volumetric concentrations up to 2%, nanoparticles diameters varying from 10 to 235 nm and fluid temperatures ranging from 10 to 90°C. The correlations proposed in this work predicted the database with a mean error of 2.94% for the thermal conductivity and 6.14% for the viscosity. The new correlation for thermal conductivity predicted the database with a mean error of 2.94% and 90% of them are correlated within a mean deviation of  $\pm 5\%$ . To viscosity, a correlation proposed in this work predicted the database with a mean error of 6.14% and more than 90% of them are correlated within a mean deviation of  $\pm 15\%$ .*

**Keywords:** *nanofluid, correlation, thermal conductivity, viscosity.*

## 1. INTRODUCTION

The high heat flux dissipation in restricted spaces is one of the current engineering challenges, as highlighted by Moreira et al. (2017). One of the heat transfer intensification techniques that was intensively investigated in the last two decades is use of nanofluids as working fluids (Ghadimi, Saidur, and Metselaar 2011; Behi 2012). The nanofluids, first proposed by Choi and Eastman (1995), and consists of the addition of nanoparticles into a base fluid in order to improve its thermal conductivity ( $k$ ) and, consequently, the heat transfer coefficient in convective heat transfer processes. Although, authors (Heyhat et al. 2013; Ho and Lin 2014; Ghanbarpour, Bitaraf Haghighi, and Khodabandeh 2014) have found the increment also in the dynamic viscosity ( $\mu$ ) of the solution in relation to the base fluid with the addition of the nanoparticles, implying in the increment of the pumping power.

The thermal conductivity and dynamic viscosity of nanofluids has been extensively studied in experimental and theoretical works over the last two decades because their direct relation with the heat transfer coefficient and pressure drop, as highlighted by Namburu et al. (2007). Besides the classical models, Maxwell (1873) and Hamilton and Crosser (1962) for the thermal conductivity and Einstein (1956) for the viscosity, several predictive methods were proposed for  $k$  and  $\mu$ . In general, methods were proposed because the classical models present reasonable predictions only for volumetric concentrations lower than 1% (P. Kumar, Kumar, and Suresh 2012; Ghadimi, Saidur, and Metselaar 2011; J.-H. Lee et al. 2011).

In general, predictive methods recently proposed, although consider effects related to the dimension of the nanoparticles, not seen in the classical models because they are based on microparticles, as the Brownian motion, does not have a solid and wide database that reduces the applicability of the method.

This work concerns the development of correlations for the  $k$  and  $\mu$  based on a large and wide database with volumetric concentrations up to 2%, nanoparticles diameters varying from 10 to 235 nm and fluid temperatures ranging from 10 to 90°C. The correlations were proposed by using the Vaschy–Buckingham theorem, procedure that resulted in accurate predictive methods as the ones of Stephan and Abdelsalam (1980) for the pool boiling heat transfer coefficient, Corcione (2011) and Mallick, Mishra, and Kundan (2013) for viscosity and conductivity of nanofluids.

## 2. METHODOLOGY

In this work, to develop the proposed correlations the Pi of Buckingham theorem was used. This theorem consists of constructing  $n$  independent dimensionless numbers,  $\pi_n$ , with the physical parameters that are related to the phenomenon currently studied, which in this case are the prediction of the thermal conductivity and dynamic viscosity of nanofluids. Then a relation between them are made and coefficients are empirically adjusted through a database.

### 2.1 Dimensionless

In his broad literature review, Wink (2015) suggested 14 dimensionless numbers to represent the thermal conductivity and dynamic viscosity, as follows (equation 1):

$$\begin{array}{cccc}
 \pi_1 = \frac{k_{nf}}{k_{bf}} & \pi_2 = \frac{\mu_{nf}}{\mu_{bf}} & \pi_3 = \phi & \pi_4 = \frac{T}{T_{crit}} \\
 \pi_5 = \frac{d_p}{d_f} & \pi_6 = \frac{k_p}{k_{bf}} & \pi_7 = \frac{\rho_{nf}}{\rho_{bf}} & \pi_8 = \frac{c_{p,nf}}{c_{p,bf}} \\
 \pi_9 = Pr_p & \pi_{10} = Pr_{bf} & \pi_{11} = \frac{Re_p}{\sqrt{N_{BRp}}} & \\
 \pi_{12} = \frac{Re_{bf}}{\sqrt{N_{BRp}}} & \pi_{13} = Re & \pi_{14} = Re_{browniano} & 
 \end{array} \quad (1)$$

Table 1 presents the parameters directly or indirectly used in the arrangement of the dimensionless numbers presented in Eq. 1. In this dimensionless numbers the subscript  $bf$  refers to the base fluid,  $nf$  to the nanofluido and  $p$  to the nanoparticle. The density,  $\rho_{nf}$ , and specific heat,  $c_{p,nf}$ , of the nanofluid are determined according to the mixing rule, as follows, equations 2 and 3, respectively:

$$\rho_{nf} = (1-\phi)\rho_{bf} + \rho_p\phi \quad (2)$$

$$c_{p,nf} = \frac{(1-\phi)\rho_{bf}c_{p,bf} + \phi\rho_p c_{p,p}}{\rho_{nf}} \quad (3)$$

The Prandtl number can be referred by the properties of the nanoparticles or of the base fluid, as it follows:

$$Pr_p = \frac{\mu_{bf} \cdot c_{p,p}}{k_p} \quad (4)$$

$$Pr_{bf} = \frac{\mu_{bf} \cdot c_{p,bf}}{k_p} \quad (5)$$

The dimensionless number  $\pi_{11}$ , given as function of the particle Reynolds, is given as the following:

$$\pi_{11} = \left( \frac{\rho_{p,d_p}}{\mu_{bf}} \right) \left( \frac{\mu_{bf}}{k_{p,T}} \right)^{-0,5} \quad (6)$$

**Table 1** – Parameters used to determine the dimensionless numbers.

Symbol	Parameter	Units
$\emptyset$	Volumetric fraction ( $\emptyset$ )	Adimensional
$d_f$	Diameter of the nanoparticle ( $d_p$ )	L
$d_p$	Thermal conductivity of the nanoparticle ( $k_p$ )	L
$k_p$	Thermal conductivity of the nanoparticle ( $k_{bf}$ )	M.L <sup>2</sup> /t <sup>3</sup>
$k_{bf}$	Temperature of the base fluid ( $T$ )	M.L <sup>2</sup> /t <sup>3</sup>
T	Critical temperature ( $T_{crit}$ )	T
$T_{crit}$	Density of the nanoparticle ( $\rho_p$ )	T
$\rho_p$	Density of the nanofluid ( $\rho_{nf}$ )	M/L <sup>3</sup>
$\rho_{nf}$	Density of the base fluid ( $\rho_{bf}$ )	M/L <sup>3</sup>
$\rho_{bf}$	Specific heat of the nanoparticle ( $c_{p,p}$ )	M/L <sup>3</sup>
$c_{p,p}$	Specific heat of the nanofluid ( $c_{p,nf}$ )	L <sup>2</sup> /t <sup>2</sup> .T
$c_{p,nf}$	Specific heat of the base fluid ( $c_{p,bf}$ )	L <sup>2</sup> /t <sup>2</sup> .T
$c_{p,bf}$	Dynamic viscosity of the base fluid ( $\mu_{bf}$ )	L <sup>2</sup> /t <sup>2</sup> .T
$\mu_{bf}$	Average free path of a molecule ( $l_{bf}$ )	M/L.t
$l_{bf}$	Boltzmann constant ( $K_b$ )	L
$K_b$	Kinematic viscosity of the base fluid ( $\nu_{bf}$ )	L <sup>2</sup> .M/t <sup>2</sup> .T
$\nu_{bf}$	Molarity of the base fluid ( $M_f$ )	L <sup>2</sup> /t
$M_f$	Avogadro number ( $N$ )	Kmol/M
N	Volumetric fraction ( $\emptyset$ )	1/mol

Similarly, the dimensionless number  $\pi_{12}$ , which is a function of the Reynolds of the base fluid, is given by the following relation:

$$\pi_{12} = \left( \frac{\rho_{bf} \cdot d_p}{\mu_{bf}} \right) \left( \frac{\mu_{bf}}{k_{p,T}} \right)^{-0.5} \quad (7)$$

The Reynolds number relative to fluid motion is defined as it follows:

$$Re = \frac{\rho_{bf} K_b T}{3\pi \mu_{bf}^2 l_{bf}} \quad (8)$$

and the Reynolds number relative to the Brownian motion by the following equation:

$$Re_{Browniano} = \frac{1}{\nu_{bf}} \cdot \sqrt{\frac{18K_b T}{\pi \rho_p d_p}} \quad (9)$$

## 2.2 Database

Table 2 presents the works, published from 2013 to 2018, used to obtain the database for the thermal conductivity and viscosity of alumina/water nanofluids. The diameters of the nanoparticles ranged from 10 to 200 nm, fluid temperature from 10-90°C and volumetric concentrations up to 13.89%.

**Table 2** – Experimental works involving the thermal conductivity and viscosity of alumina/water nanofluids.

Author	d [nm]	Vol. Concentration [%]	Prepare method	Analysis method	Temperature
Gavili et al. (2013)	36±7	1 a 3%	Two Step	KD2 pro (conductivity) Viscosímetro DV-II PRO (viscosidade)	25 a 40 °C
Said et al. (2013)	13	0.05-0.1%	Two Step	KD2 pro (conductivity) Viscosímetro DV-II PRO (viscosidade)	25°C (conductivity); 20 a 50°C (viscosidade)
Tiwari, Ghosh. and Sarkar (2013)	45	1 a 3%	Dilution/Two Step	KD-2 Fio quente transiente. viscosímetro LVDV-II+Pro	40 °C
Heyhat et al. (2013)	40	0.1 a 2%	Two Step	KD2 pro (conductivity) Viscosímetro capilaridade - Petrotest	20 a 60 °C
Ho and Chen (2013)	33	0 - 2.78%	Two Step	KD2 Pro e Viscosímetro DV-II PRO	30 °C
Ghanbarpour, Bitaraf Haghigi. and Khodabandeh (2014)	75	0.83-13.89%	Dilution/Two Step	Sonda TPS 2500 e Viscosímetro DV-II PRO	20 a 50 °C
Hachey et al. (2014)	10	1 a 5%	Dilution/Two Step.	KD2PRO e Viscolab 4000	25 a 55 °C
Ho and Lin (2014)	33	0.56-2.98%	Dilution/Two Step	KD2 Pro e Viscosímetro DV-II PRO	20 0 60 °C
J. H. Lee. Lee. and Pil Jang (2014)	71.6 . 114.5 e 136.8	0.51%	Two Step.	Método de fio quente transiente (somente conductivity)	10 a 80 °C
Darzi, Farhadi. and Sedighi (2014)	20	0.25-1.0%	Two Step	Viscolite 2700 KD2	25 a 55 °C
Mojarrad et al. (2014)	20 a 30	0.25-0.7%	Two Step and surfactant	KD2 Pro e viscosímetro DV-II PRO	20 a 50 °C
Cao, Ding. and Ma (2014)	100 e 200	1.14- 5.56%	Two Step	Lambda System PSL e reometro MCR 301	20 a 50 °C
Sekhar and Sharma (2015)	47	0.01-1.0%	Two Step and surfactant	viscosímetro R/S-CPS+	20 a 45 °C
Ghanbarpour et al. (2015)	235	1.39-2.77%	Two Step and surfactant	HotDisk model 2500 e DV-II + PRO	18 a 48 °C
Xia et al. (2016)	5	0.1-1.0%	Two Step and surfactant	viscosímetro HAAKE VT 550	28 °C
Saxena, Gangacharyulu. and Bulasara (2016).	40	0-0.5%	Two Step	KD2 Pro e viscosímetro tipo Ubbelohde	27 a 75 °C
Vijayakumar. Navaneethakrishnan. and Kumaresan (2016)	37.5	0.14 - 0.41%	Two Step	KD2 Pro e viscosímetro Brookfield (S-18)	30 a 90°C
Colla et al. (2016)	43	1 - 3%	Dilution/Two Step	Sonda TPS 2500 s e Reometro AR-G2	20 e 25 °C
Agarwal et al. (2017)	53	0 - 2.00%	Two Step	KD2 PRO	10 a 70 °C
N. Kumar, Sonawane. and Sonawane (2018)	10	0.01 a 0.08 %	Two Step	KD2 PRO	30 a 50 °C
Elcioglu et al. (2018)	10 e 30	1 a 3%	Dilution/Two Step	Viscosímetro VS-10	20 a 50 °C

### 2.3 2.3 Data analysis and method development

In this work were adopted the coefficients adjustment method proposed by Wink (2015). In this method the dimensionless numbers with higher correlation are obtained through the minimum square method. To evaluate the accuracy of the correlations, the mean error was calculated, as it follows:

$$\text{Mean deviation} = \frac{1}{n} \sum_{i=1}^n \left| \frac{(Exp - corr)}{Exp} \right| \quad (10)$$

Also, comparisons between the data available for the thermal conductivity were compared with the correlations of Maxwell (1873) (equation. 11), Chon et al. (2005) (equation 12) e de Wink (2015) (equation 13).

$$\frac{k_{nf}}{k_{bf}} = \frac{k_p + 2k_{bf} + 2\phi(k_p - k_{bf})}{k_p + 2k_{bf} - \phi(k_p - k_{bf})} \quad (11)$$

$$\frac{k_{nf}}{k_{bf}} = 1 + 64,7\phi^{0,746} \left(\frac{d_f}{d_p}\right)^{0,369} \left(\frac{K_p}{K_f}\right)^{0,7476} Pr^{0,9955} Re^{1,2321} \quad (12)$$

$$\frac{k_{nf}}{k_{bf}} = 1 + 1,83 \cdot 10^{-4} \phi^{0,9223} \left(\frac{d_f}{d_p}\right)^{0,4135} Re_{browniano}^{-0,6136} Pr_p^{-2,2558} \quad (13)$$

To viscosity, the comparisons occurred between the correlations the Einstein (1956) (equation 14), Corcione (2011) (equation 15) and Wink (2015) (equation 16).

$$\frac{\mu_{nf}}{\mu_f} = 1 + 2,5\phi \quad (14)$$

$$\frac{\mu_{nf}}{\mu_f} = \frac{1}{1 - 34,87\left(\frac{d_p}{d_f}\right)^{-0,3} \phi^{1,03}} \quad (15)$$

$$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 13,933\phi^{0,5297} \left(\frac{d_f}{d_p}\right)^{0,5685} \left(\frac{\rho_{nf}}{\rho_{bf}}\right)^{7,9145} \quad (16)$$

### 3. RESULTS AND DISCUSSION

#### 3.1 Thermal conductivity

As Shown in Table 3, 264 experimental results for the thermal conductivity were obtained from the literature. Through the database, and the procedure proposed by Wink (2015), the following relation was developed to predict the thermal conductivity:

$$\frac{k_{nf}}{k_{bf}} = 1 + 3,372 \cdot (\phi)^{0,054} \left(\frac{k_p}{k_{bf}}\right)^{-0,71} \left(\frac{\rho_{nf}}{\rho_{bf}}\right)^{25,7} (Re_{browniano})^{0,392} \quad (17)$$

Table 4 presents the comparison between the predictive methods indicated in section 2.3, the new one and the experimental data extracted from the literature. As noted in the table, the correlation developed in this work provided the best results, predicting the data with a mean error of 2.94%. Also, the new method predicted 90.15% of the database within an error range of  $\pm 7\%$ . The correlation of Wink et al. (2015) also provided reasonable results, as indicated in Tab. 4. The worst results were obtained by the method of Maxwell (1873).

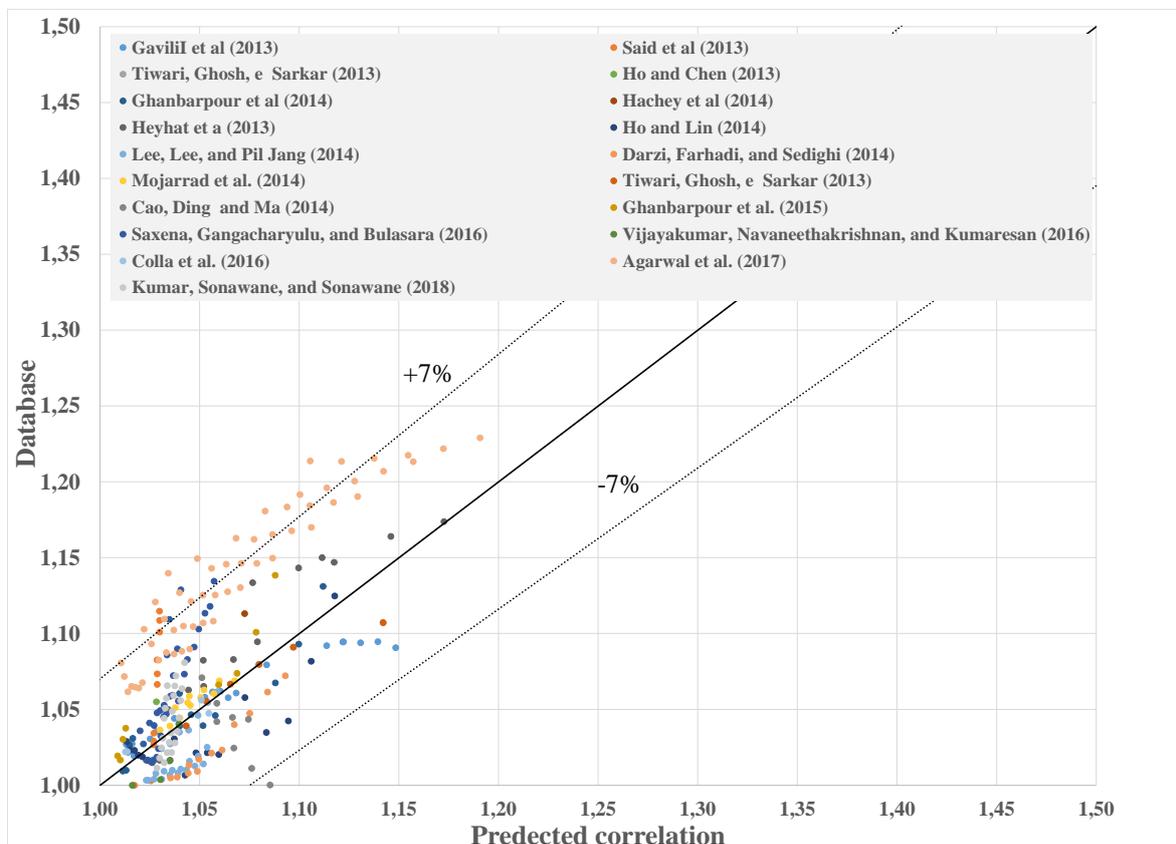
Figure 1 displays a comparison between the experimental data and predictions considering the new correlation. As observed, in general the proposed correlation predicts correctly the experimental data extracted from the literature. The only deviation is observed for the data from Agarwal et al. (2017). It is worth to highlight that these authors used commercial diluted nanofluids, what may explain the discrepancy in the results.

**Table 3** – Experimental results extracted from the literature.

Author	Experimental results
Gavili et al (2013)	22
Heyhat et a (2013)	16
Said et al (2013)	11
Tiwari, Ghosh, e Sarkar (2013)	6
Ho and Chen (2013)	1
Lee, Lee, and Pil Jang (2014)	24
Ho and Lin (2014)	15
Ghanbarpour et al (2014)	12
Darzi, Farhadi, and Sedighi (2014)	12
Mojarrad et al. (2014)	12
Cao, Ding and Ma (2014)	8
Ghanbarpour et al. (2015)	8
Saxena, Gangacharyulu, and Bulasara (2016)	31
Vijayakumar, Navaneethakrishnan, and Kumaresan (2016)	4
Colla et al. (2016)	4
Agarwal et al. (2017)	55
Kumar, Sonawane, and Sonawane (2018)	23

**Table 4** – Comparison between the experimental database and correlations to conductivity.

Correlation	Mean error	Data with mean error smaller than 7%
Proposed correlation (Equation 17)	2.94%	90.15%
Maxwell (1973)	10.55%	36.74%
Chon et al. (2014)	6.84%	62.88%
Wink (2015)	3.90%	82.58%



**Figure 1** – Comparison between the experimental data and the predictions according to the new correlation.

### 3.2 Viscosity

A total of 258 experimental data were extracted from the literature for the dynamic viscosity. Table 5 indicates the distribution of the data according to each work used.

**Table 5** – Experimental results extracted from the literature.

Author	Experimental results
Gavili et al (2013)	21
Heyhat et a (2013)	24
Ho and Chen (2013)	5
Said et al (2013)	7
Tiwari, Ghosh, e Sarkar (2013)	6
Cao, Ding and Ma (2014)	2
Darzi, Farhadi, and Sedighi (2014)	32
Ghanbarpour et al (2014)	12
Hachey et al (2014)	7
Ho and Lin (2014)	15
Mojarrad et al. (2014)	12
Ghanbarpour et al. (2015)	8
Sekhar and Sharma (2015)	30
Colla et al. (2016)	4
Saxena, Gangacharyulu, and Bulasara (2016)	33
Vijayakumar, Navaneethakrishnan, and Kumaresan (2016)	21
Xia et al. (2016)	3
Elcioglu et al. (2018)	16

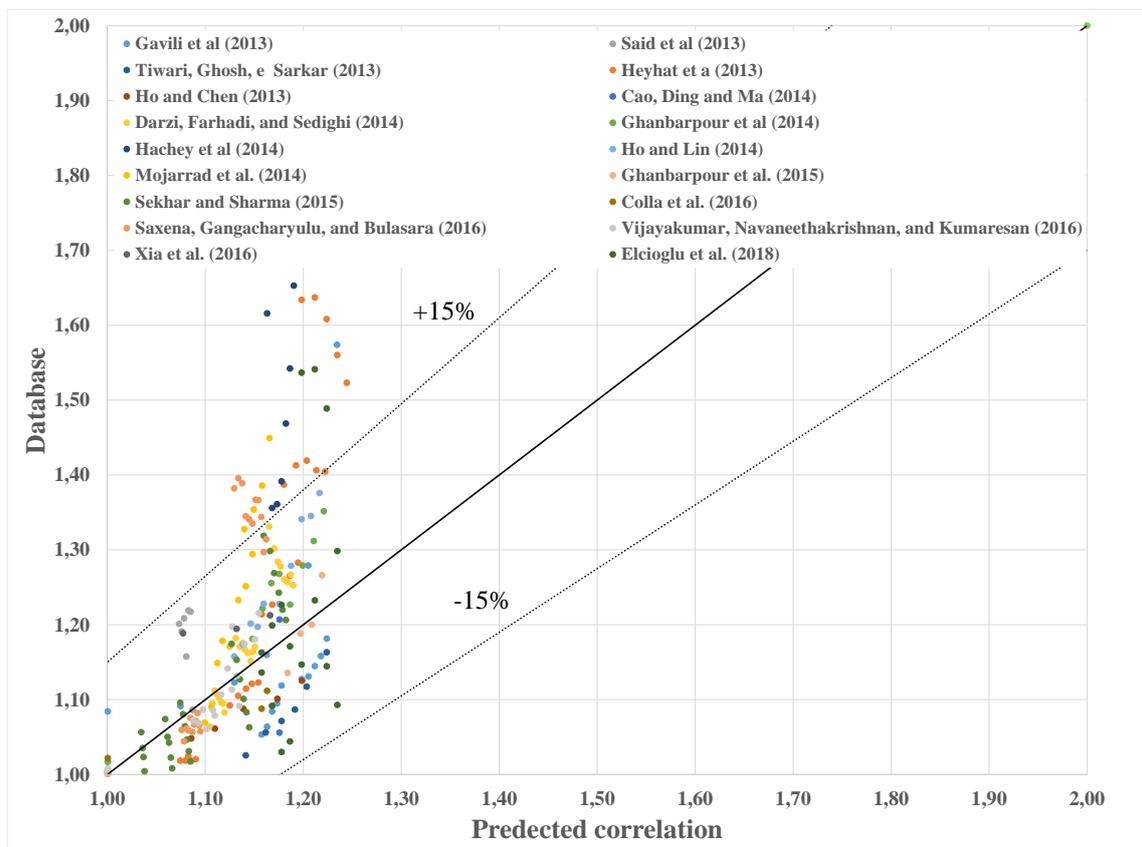
Based on the database showed in Table 5 and on the development suggested of Wink (2015), a new correlation was proposed for the prediction of the dynamic viscosity of alumina nanofluids, as it follows:

$$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 0,172 \cdot (\phi)^{0,332} Pr_p^{-0,371} \quad (18)$$

Table 6 shows a comparison between the experimental database and the new correlation and others indicated in section 2.3. The new proposed correlation was the one the best predicted the experimental data, presenting a mean error of 6.14% and predicting 90.31% of the data within an error range of  $\pm 15\%$ . As for the thermal conductivity, the correlation developed by Wink (2015) was the second on that best predicted the experimental data. Figure 2 illustrates the comparison between the proposed correlation and the experimental database. According to this figure, the correlation fails in the predictions of the viscosity of nanofluids which viscosity is 20% higher than for the base fluid. One possible reason is the fact that the nanofluids presents for larger concentrations a non-Newtonian rheological behavior.

**Table 6** – Comparison between the experimental database and predictive methods.

Predictive method	Mean error	Data with mean error smaller than 15%
Proposed correlation (equation 18)	6.14%	90.31%
Einstein (1906)	37.79%	11.63%
Corcione (2014)	35.55%	13.18%
Wink (2015)	7.74%	82.56%



**Figure 2** – Comparison between the experimental data and the predictions according to the new correlation.

#### 4. CONCLUSIONS

In this work it was developed two new correlations, one for the thermal conductivity and other for the dynamic viscosity, both for alumina nanofluids based on experimental results extracted from the literature. The development of the correlations was done based on the Vaschy–Buckingham theorem.

The correlation developed for the thermal conductivity predicted 90.1% of the experimental data within an error range of  $\pm 7\%$ , presenting a mean error of only 2.9%. The dynamic viscosity correlation predicted 90.3% of the experimental data within an error range of  $\pm 15\%$ , presenting a mean error of 6.1%. In both cases the correlations developed in this study presented more accurate prediction in comparison with methods commonly seen in the literature compared to experimental results.

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