Numerical Investigation of the Use of a New Nano-Particle in Microchannel

Fuat Kaya (fkaya@ohu.edu.tr)
Nigde Omer Halisdemir University

Original Article

Keywords: Microchannel, Nanofluid, CFD, Pressure drop, Heat Transfer, Boron nitride

Posted Date: May 26th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-513728/v1

Abstract

The purpose of this paper is to study the effects of the use of Boron nitride (BN) as nano-particle on pressure drop and heat transfer in a microchannel. The governing equations for the fluid flow were solved by using Fluent CFD code and artificial neural network (ANN). Computational results acquired from Fluent CFD code and artificial neural network (ANN) for alumina (Al_2O_3) as nano-particle were compared with numerical values obtained in the literature for validation. On the basis of a water-cooled (only water, water+alumina and water+boron nitride) smooth microchannel were designed, and then the corresponding laminar flow and heat transfer were studied numerically.

Results derived from the numerical tests (NT) and artificial neural network (ANN) show good agreement with the values mentioned in the literature and these results also show by the comparison research which was conducted considering the heat transfer and pressure loss parameters between BN and widely used alumina that BN is more convenient nano-particle.

1 Introduction

Microchannels are fluid flow channels with small hydraulic diameters. Following the classification by Kandlikar and Grande [1], channels with a minimum cross-sectional dimension between 200 μm and 3 mm are classified as minichannels and between 1 μm and 200 μm are classified as microchannels. The flow in microchannels has been the topic of increased research interest over the past years. It is seen in many important applications, such as miniature heat exchangers, microscale process units, research nuclear reactors, materials processing and thin film deposition technology, biotechnology system as well as in potential space application [2]. A lot of research has been done to improve thermal performance on micro systems in literature [3–7].

Kaya [5] researched the effects of ramification length and angle on pressure drop and heat transfer in a ramified microchannel. Results derived from the numerical tests indicate that the pressure drop increases with increasing both the ramification length and angle. Furthermore, the highest temperature inside the ramified microchannel increases with increasing the ramification length as well as increasing the ratio volume fraction of ethanol.

Zunaid et al. [8] studied the heat transfer and pressure drop characteristics of a straight rectangular and semi cylindrical projections microchannel heat sink. And, they stated that heat transfer increases with the use of semi cylindrical projections microchannel heat sink.

It is hard to cool the heated system with traditional liquids owing to the high power and high integration demand, so researchers concentrated on nanofluids.

Nanofluids are substances gained by suspending solid particles in a fluid. These fluids are usually water-based, considering thermal performance.

Sabaghan et al. [9] researched a comprehensive numerical procedure which is based on the two-phase approach to simulate a rectangular microchannel consisting of six longitudinal vortex generators (LVGs), and stated that using the mixture of EG:W (60:40 ethylene glycol and water) instead of pure water as a base-fluid leads to the increase of heat transfer in the microchannel. Finally, the maximum normalized efficiency of the LVG-enhanced microchannel, compared to the plain channel, is around 14%. Furthermore, using nanofluid can improve the normalized efficiency by 27%.

Abdolahi et al. [10] investigated the fluid flow and heat transfer characteristics of laminar nanofluid flow in microchannel heat sink (MCHS) with V-Type inlet/outlet arrangement, and showed that nanofluid can improve the performance of MCHS with V-shaped inlet/outlet arrangement.

Belhadj et al. [11] researched a numerical study of laminar forced convective flow of nanofluid-based water/Al_2O_3 in a two-dimensional horizontal microchannel heat sink. And, they mentioned that their work contributes to ameliorate the cooling systems by integrating the nanofluids in the next generation of microchannels heat sinks.

Shi et al. [12] created a new simulation method which is proposed in their paper to consider that the nanofluids thermophysical properties is nonuniform and dynamic in the channels. It was validated by the classical experimental data. The effects of the nanoparticles concentration, Reynolds number and axial thermal conduction effect on the flow and heat transfer characteristics of nanofluids in microchannels are analyzed. They said that the proposed numerical simulation method can simulate the forced flow and heat transfer of nanofluids in the microchannel more accurately than the traditional single-phase model.

Studies on the effects of Boron minerals as nanofluids are very limited in numbers in the literature in spite of the fact that these minerals are significant for cooling systems. Furthermore, the presence of new nanofluids is considerable to do away with the troubles of cooling systems.

Hou et al. [13] showed a new nanofluid called Boron nitride nanosheets considering thermal performance.

In this study, to acquire the effect of the use of Boron nitride as nano-particle in a microchannel on pressure drop and heat transfer, the 3-D numerical simulations by using Fluent CFD code and artificial neural network (ANN) of the microchannels for different volume fraction of nanofluid were assessed. The geometrical dimensions researched in this paper are demonstrated in Ref. Shi et al. [12]. Boron nitride and Alumina as nano-particle are utilized with water as base fluid by changing inlet Reynolds numbers. And, which of these two nanoparticles have better properties in terms of pressure drop and heat transfer characteristics was judged.

2 Material And Method

2.1 Numerical model

Governing equations for incompressible, steady state and laminar flow in a microchannel were calculated numerically using Fluent CFD code.

The steady-state conservation of mass, momentum and energy equations can be shown in the following compact form [5]:

$$\nabla.(\rho \vec{U}) = 0 \tag{1}$$

$$\vec{U}.\nabla(\rho \vec{U}) = -\nabla P + \nabla.(\mu \nabla \vec{U}) \tag{2}$$

$$\vec{U}.\nabla(\rho c_p T) = \nabla.(k \nabla T) \tag{3}$$

For the simulations, a uniform heat flux of 200 000 W/cm^2 was applied on the bottom surface of the substrate. The top wall surface of the channels and the outer surfaces of the microchannel were accepted to be insulated. For the flow field, the velocity applied at the inlet was assumed to be uniform and a pressure condition was applied at the outlet.

The microchannel utilized in the numerical tests (NT) has overall length of 44.8 mm and the hydraulic diameter of 341 μm while other geometric parameters can be found in Shi et at. [12].

The numerical computation was done with a numerical grid shown in Fig. 1, where the white color shows the regions of very frequent mesh.

Different grades of grid refinement were tested. The grid refinement research demonstrated that a total number of about 3399973 elements was sufficient to acquire a grid-independent solution. The properties of the nanofluid of Alumina and the pure water in detail can be seen in Shi et al. (2018). Some properties of Boron nitride (BN) nanofluid such as density, specific heat and thermal conductivity are 2300 kg/m^3, 1150 J/kgK and 52 W/mK, respectively.

2.2 Artificial Neural Network Model

In order to model the given governing equations, a neural network model is constructed in MATLAB which is shown in the Fig. 2. This model has five inputs, one hidden layer with ten neurons and two outputs. Hidden layer neurons has the activation function of hyperbolic tangent sigmoid transfer function.

Training of the neural network is chiefly based on two groups of data. Former group is derived from numerical computations. Second collection of data pairs are directly taken from the reference [12].

In MATLAB there is a toolbox named as “fitting app” that is used to form and train a neural network model. The obtained results are combined and supported to the fitting application as inputs and targets. Seventy percent of this data are used for training, fifteen percent are used for validation and the rest are used for testing the trained model. The training algorithm is selected as Levenberg-Marquardt due to its low convergence speed to the best result.

Fitting app exports an input-output static m-file function. Hence, an alternative way of computing equations that governs numerical models without repeating, is obtained. After successful completion of network training same input data are applied to the network and the outputs are obtained.

Neural network outputs are pretty match up with numerical results.

3 Results And Discussion

In this paper, to obtain the effect of the use of Boron nitride as nano-particle in a microchannel on pressure drop and heat transfer, the 3-D numerical simulations by using Fluent CFD code and artificial neural network (ANN) of the microchannels for different volume fraction of nanofluid were assessed. The geometrical dimensions studied in this paper are shown in Ref. Shi et al. [12]. Boron nitride and Alumina as nano-particle are used with water as base fluid by changing inlet Reynolds numbers. Which of these two nanoparticles were considered to have superior properties in terms of pressure drop and heat transfer characteristics was evaluated.

At first, numerical technique was verified with results given in Shi et al. [12]. The inlet temperature of fluid had a constant value of 303.15 K for different Reynolds numbers. A uniform heat flux, q=200000 W/cm^2, was applied to the bottom surface of the microchannel.

Fig. 3 shows the comparison of the pressure drop values for different Reynolds numbers obtained through the numerical tests (NT) and artificial neural network (ANN) with the results given in Shi et al. [12].

As can be seen from Fig. 3, the pressure drop increases with the increasing Reynolds numbers, so it can be seen clearly that the consumption of pumping power directly increases. Moreover, the pressure drop also increases owing to the increase of the mixture density with the addition of 1% and 3% Al_2O_3 as nano-particle. Results obtained from the numerical tests (NT) and artificial neural network (ANN) show good agreement with results given in Shi et al. [12].

Fig. 4 gives the comparison of the heat transfer coefficients values for different Reynolds numbers obtained by the numerical tests (NT) and artificial neural network (ANN) with the results given in Shi et al. [12].

As can be seen from Fig. 4, the heat transfer coefficient increases with the increasing Reynolds number, so it is clear that the thermal performance directly increases. Moreover, the thermal performance also increases due to the improvement of the thermal properties with the addition of 1% and 3% Al_2O_3 as nano-particle. Results obtained from the numerical tests (NT) and artificial neural network (ANN) demonstrates good agreement with results given in Shi et al. [12]. Figure 5 gives the Comparison of the pressure contour obtained numerically for pure water with Re=600, 1200 and 1800, respectively.

After these validation studies, the effect of the use of Boron nitride as nano-particle in a microchannel on pressure drop and heat transfer were studied in detail.

Fig. 6 shows the relationship between the maximum temperatures of a microchannel for a range of Reynolds numbers. It can be seen that the maximum temperature decreases with the increasing Reynolds numbers since the thermal resistance decreases as the Reynolds numbers increases. This nonlinear trend is in agreement with already published papers in literature [14]. The contours of these temperature are given in Fig. 7.

Comparison of heat transfer coefficient values longitudinal development along microchannel for volume fraction=1% and 3% (for Alumina+water and BN+water) obtained by numerical tests (NT) and artificial neural network (ANN), is given Fig. 8.

As can be seen from Fig. 8, the heat transfer coefficient of BN is much higher compared with Al_2O_3 for same Reynolds numbers, because it is clear that BN compared with Al_2O_3 has high thermal properties.

Comparison of pressure drop values longitudinal development along microchannel for volume fraction=1% and 3% (for Alumina+water and BN+water) obtained by numerical tests (NT) and artificial neural network (ANN), is given in Fig. 9.

As can be seen from Fig. 9, the pressure drop values of BN is slightly lower compared with Al_2O_3 for same Reynolds numbers, as it is clear that BN compared with Al_2O_3 has low density.

These results obtained by fig. 8 and fig. 9 show that the properties of fluid pair considerably affect heat transfer and pressure drop. And, it can be concluded that the improvement of the heat transfer and pressure drop in the microchannel relates to the properties of fluid pattern.

In cooling systems, the heat transfer properties are desired to be high while the pressure loss are wanted to be minimum. The changing of geometric parameters to increase the heat transfer properties and reduce the pressure loss yields no results because the configurations which are made to make heat transfer better give rise to pressure loss. In this situation, the best thing to be done is to add new nanofluids to the literature which can replace the old nanofluids. When the relevant literature is taken into account, it is seen that alumina is the most common used nanofluids. It is seen through the comparison research which was carried out considering the heat transfer and pressure loss parameters between BN and widely used alumina that BN is more convenient nanofluid.

Fig. 10 gives the friction factor values the results obtained by numerical tests for different Reynolds numbers and pure water.

The friction coefficient decreased with the increasing Reynolds numbers, and it was almost constant at high Reynolds numbers (Fig. 10). The reason is that at low Reynolds numbers, viscous effects and friction coefficient of the fluid flow are high. Viscous effects decrease with the increasing Reynolds numbers therefore decreasing the effects of surface friction. Comparison of friction coefficients obtained numerically at different Reynolds numbers and the friction coefficient which finally become almost constant.

4 Conclusions

In this paper, to obtain the effect of the use of Boron nitride as nano-particle in a microchannel on pressure drop and heat transfer, the 3-D numerical simulations by using Fluent CFD code and artificial neural network (ANN) of the microchannels for different volume fraction of nanofluid were assessed. The geometrical dimensions studied in this paper are given in Ref. Shi et al. [12]. Boron nitride and Alumina as nano-particle are used with water as base fluid by changing inlet Reynolds numbers. And, which of these two nanoparticles have superior properties in terms of pressure drop and heat transfer characteristics was evaluated.

Results obtained from the numerical tests (NT) and artificial neural network (ANN) show good agreement with the values given in the literature.

The pressure drop increases with the increasing Reynolds numbers, so it is clear that the consumption of pumping power directly increases. Moreover, the pressure drop also increases due to the increase of the mixture density with the addition of 1% and 3% nano-particle.

The heat transfer coefficient increases with the increasing Reynolds number, so it is clear that the thermal performance directly increases. Moreover, the thermal performance also increases due to the improvement of the thermal properties with the addition of 1% and 3% nano-particle.

The maximum temperature decreases with the increasing Reynolds numbers because the thermal resistance decreases as the Reynolds numbers increases. This nonlinear trend is in agreement with already published work in literature [14].

The properties of fluid pair significantly affect heat transfer and pressure drop. And, it can be concluded that the improvement of the heat transfer and pressure drop in the microchannel relates to the properties of fluid pattern.

It is seen through the comparison research which was done considering the heat transfer and pressure loss parameters between BN and widely used alumina that BN is more convenient nano-particle.

The friction coefficient decreased with the increasing Reynolds numbers, and it was almost constant at high Reynolds numbers. The reason is that at low Reynolds numbers, viscous effects and friction coefficient of the fluid flow are high. Viscous effects decrease with the increasing Reynolds numbers decreasing thus the effects of surface friction. Comparison of friction coefficients obtained numerically at different Reynolds numbers and the friction coefficient which finally become almost constant.

Declarations

Acknowledgements

Not applicable.

Authors' Contributions

FK took all of the research work, including the literature research, modeling, results analysis, and paper writing. FK read and approved the final manuscript.

Authors' Information

Fuat KAYA, born in 1976, is currently an assistant professor at *Nigde Omer Halisdemir University, Turkey*. He received his Ph.D. degree from *Uludag University, Turkey*, in 2009. His research interests include flow and heat systems.

Funding

Not applicable.

Availability of Data and Materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing Interests

The author declare no competing financial interests.

References

1. S.G. Kandlikar and W. J. Grande. Evolution of Microchannel Flow Passages– Thermohydraulic Performance and Fabrication Technology. *Heat Transfer Engineering,* 2003, 24 (1): 3–17.
2. N. Shao, A. Gavriilidis, P. Angeli. Flow Regimes for Adiabatic Gas–Liquid Flow in Microchannels. *Chemical Engineering Science*, 2009, 64 (1): 2749-2761.
3. P. Bermejo, R. Revellin, R. Charnay, O. Garbrecht, J. Hugon, J. Bonjour. Modeling of a Microchannel Evaporator for Space Electronics Cooling:Entropy Generation Minimization Approach. *Heat Transfer Engineering,*2013, 34 (4): 303-312.
4. L. Gong, J. Zhao, S. Huang. Numerical Study on Layout of Micro-Channel Heat Sink for Thermal Management of Electronic Devices. *Applied Thermal Engineering*, 2015, 88 (1): 480-490.

5. F. Kaya. Numerical Investigation of Effects of Ramification Length and Angle on Pressure Drop and Heat Transfer in a Ramified Microchannel. *Journal of Applied Fluid Mechanics,* 2016, 9 (2): 767–772.
6. T. Saenen and M. Baelmans. Numerical Model of a Two-Phase Microchannel Heat Sink Electronics Cooling System *International Journal of Thermal Sciences*, 2012, 59 (1): 214–223.
7. C.S. Sharma, M. K. Tiwari, B. Michel, D. Poulikakos. Thermofluidics and Energetics of a Manifold Microchannel Heat Sink for Electronics with Recovered Tot Water as Working fluid. *International Jornal of Heat and Mass Transfer*, 2013, 58 (1-2): 135-151.
8. M. Zunaid, A. Jindal, D. Gakhar, A. Sinha. Numerical Study of Pressure Drop and Heat Transfer in a Straight Rectangular and Semi Cylindrical Projections Microchannel Heat Sink. *Journal of Thermal Engineering*, 2017, 3 (5): 1453-1465.
9. A. Sabaghan, M. Edalatpour, M. C. Moghadam, E. Roohi, H. Niazmand. Nanofluid Flow and Heat Transfer in a Microchannel with Longitudinal Vortex Generators: Two-Phase Numerical Simulation. *Applied Thermal Engineering*, 2016, 100 (1): 179-189.
10. A. Abdollahi, H. A. Mohammed, S. M. Vanaki, A. Osia, M. R. G. Haghighi. Fluid Flow and Heat Transfer of Nanofluids in Microchannel Heat Sink with V-Type Inlet/Outlet Arrangement. *Alexandria Engineering Journal,* 2017, 56 (1): 161-170.
11. A. Belhadj, R. Bouchenafa, R. Saim. Numerical Investigation of Forced Convection of Nanofluid in Microchannels Heat Sinks. *Journal of Thermal Engineering*, 2018, 4 (5): 2263-2273.
12. X. Shi, S. Li, Y. Wei, J. Gao. Numerical Investigation of Laminar Convective Heat Transfer and Pressure Drop of Water-Based Al_2O_3 Nanofluids in a Microchannel. *International Communications in Heat and Mass Transfer*, 2018, 90 (1): 111–120.
13. X. Hou, M. Wang, L. Fu, Y. Chen, N. Jiang, C. T. Lin, Z. Wang, Z. Yu. Boron Nitride Nanosheet Nanofluids for Enhanced Thermal Conductivity. *Royal sciety of chemistry,* 2018, 10 (1): 13004-13010.
14. O.T. Bello, J. P. Meyer, F. .U. Ighalo. Combined Numerical Optimization and Constructal Theory for the Design of Microchannel Heat Sinks. *Numerical Heat Transfer; Part A*, 2010, 58 (11): 882-899.

Figures

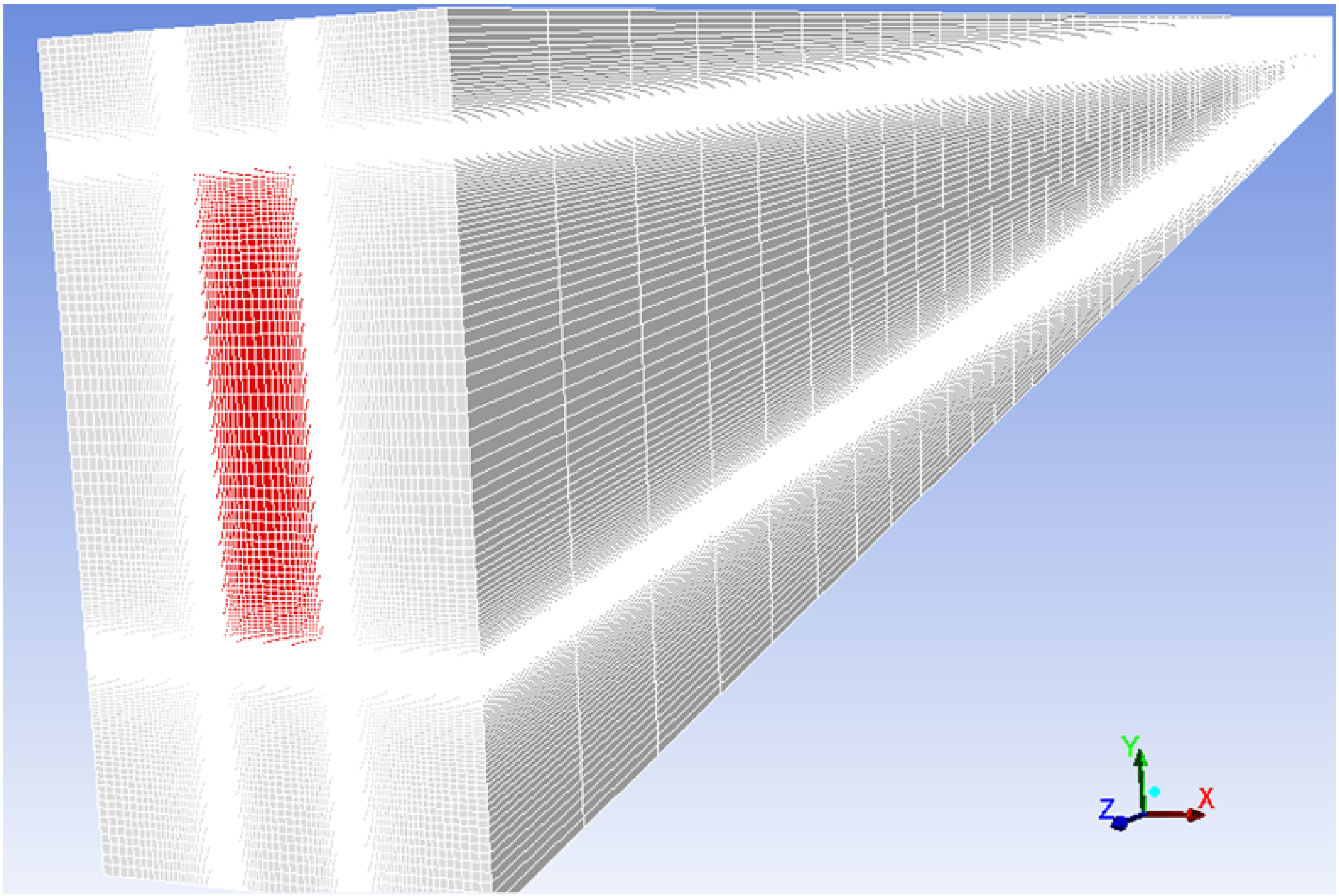

Figure 1

CFD surface mesh for the microchannels

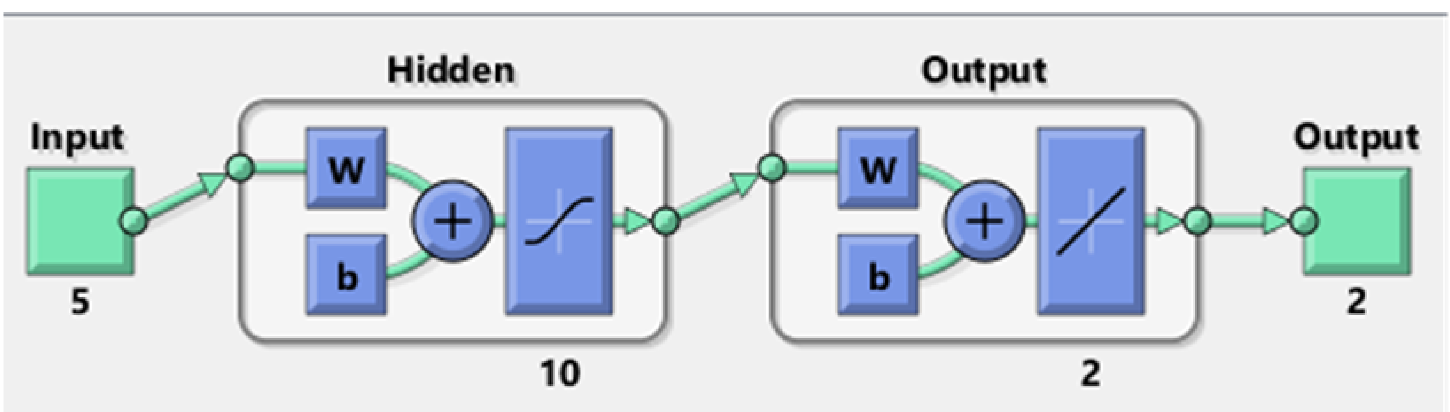

Figure 2

Internal schema of the network.

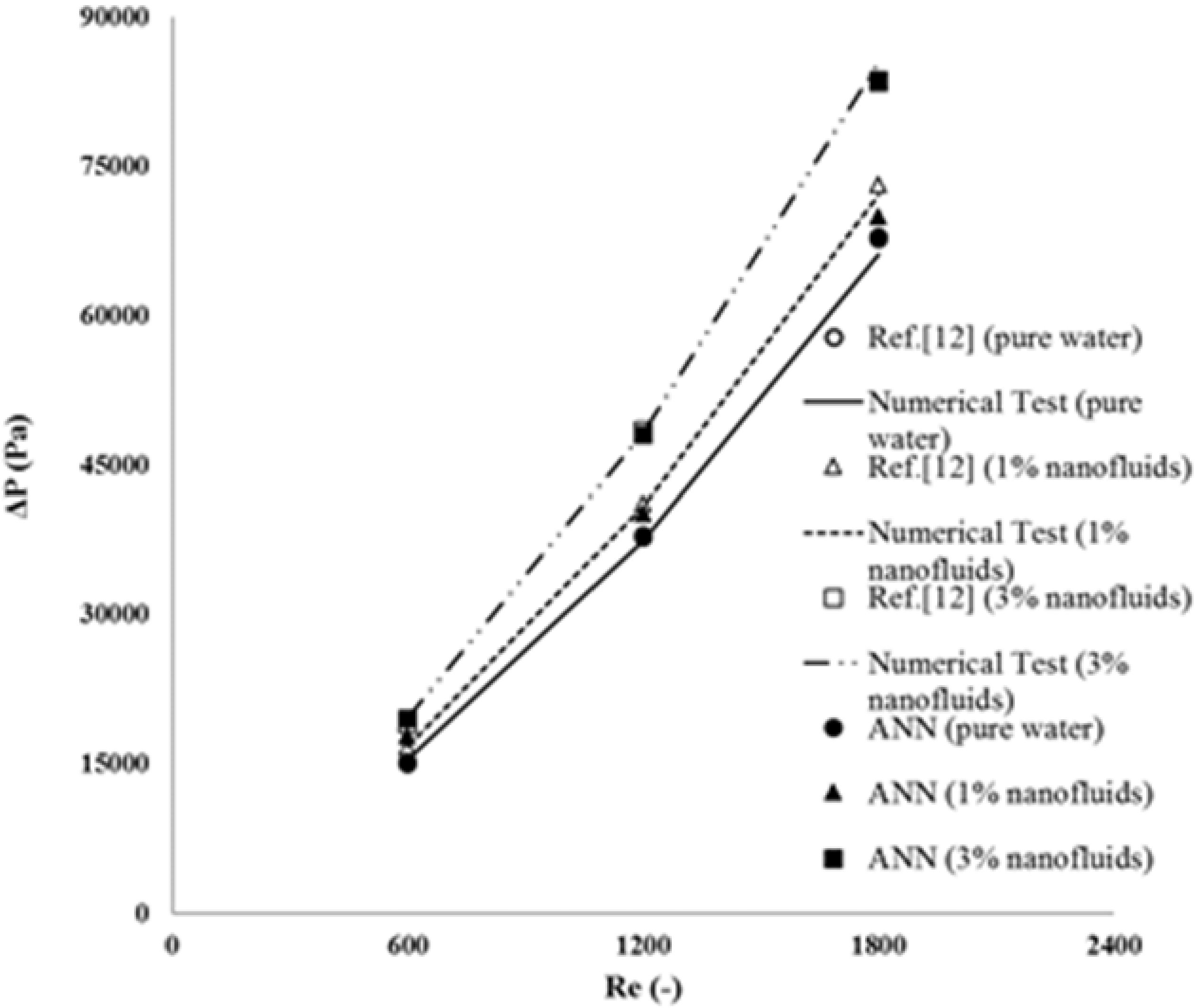

Figure 3

Comparison of the pressure drop values for different Reynolds numbers obtained by the numerical tests (NT) and artificial neural network (ANN) with the results given in Shi et al. [12].

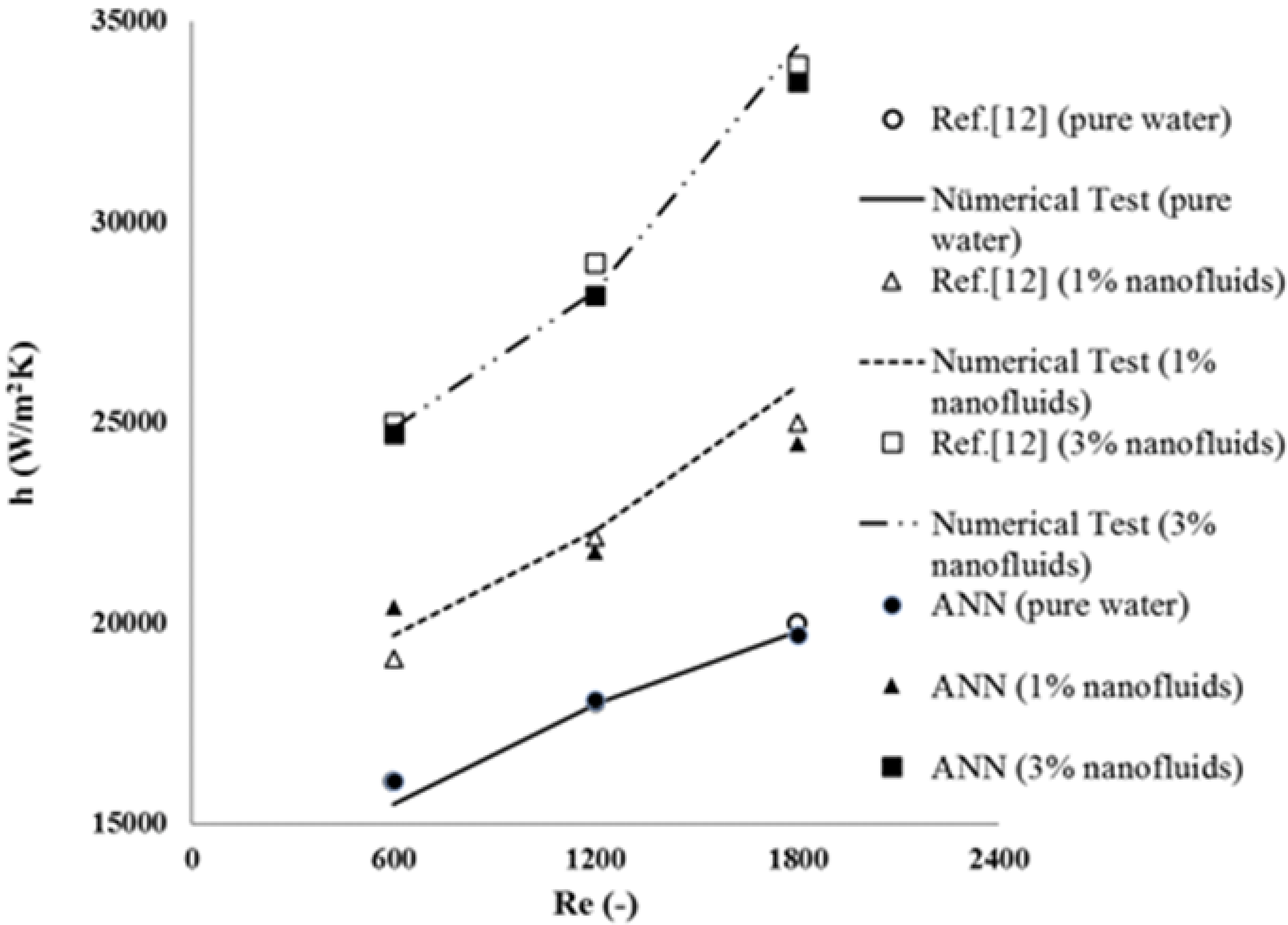

Figure 4

Comparison of the heat transfer coefficients values for different Reynolds numbers obtained by the numerical tests (NT) and artificial neural network (ANN) with the results given in Shi et al. [12].

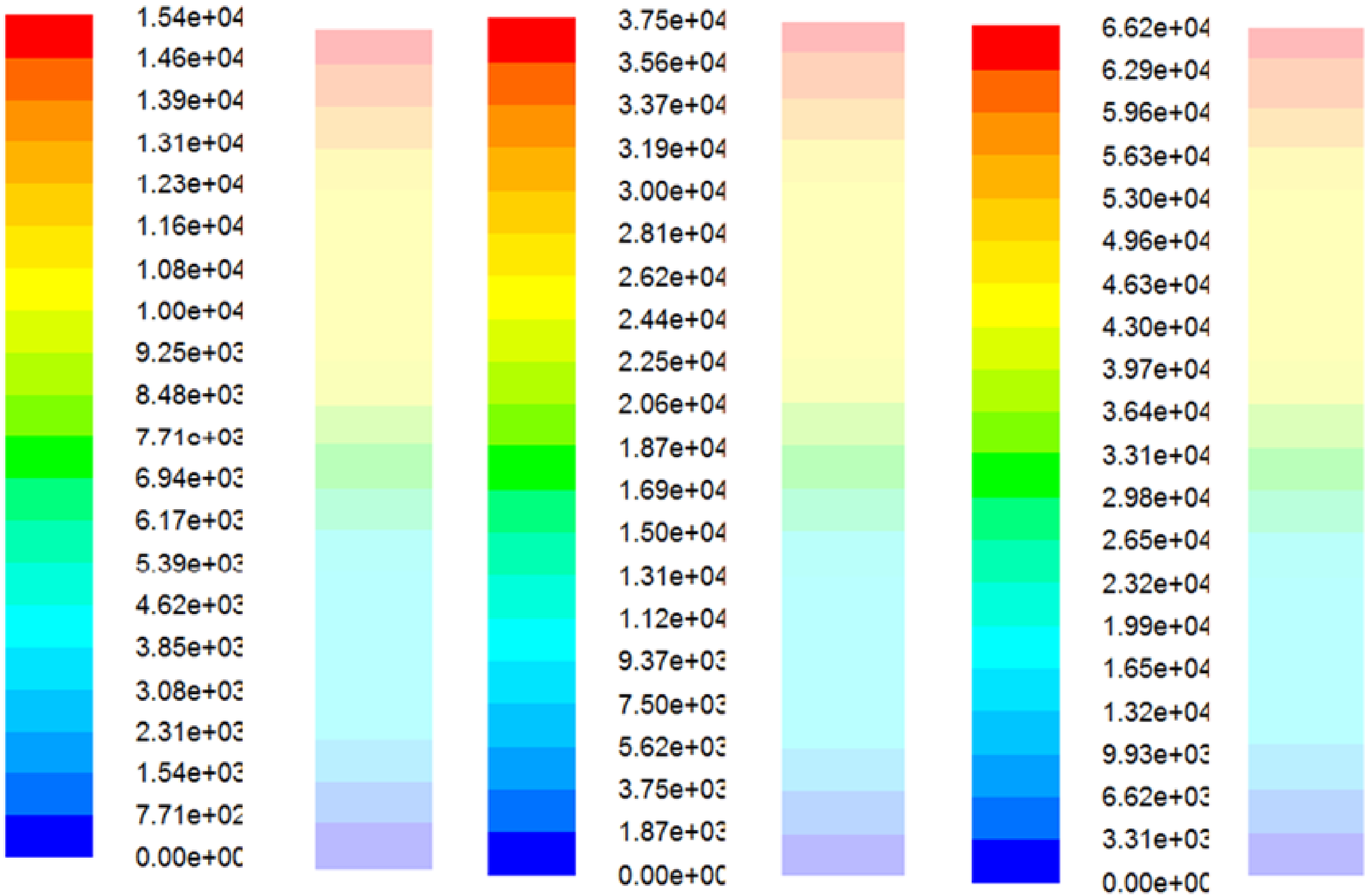

Figure 5

Comparison of the pressure contour obtained numerically for pure water with Re=600, 1200 and 1800, respectively.

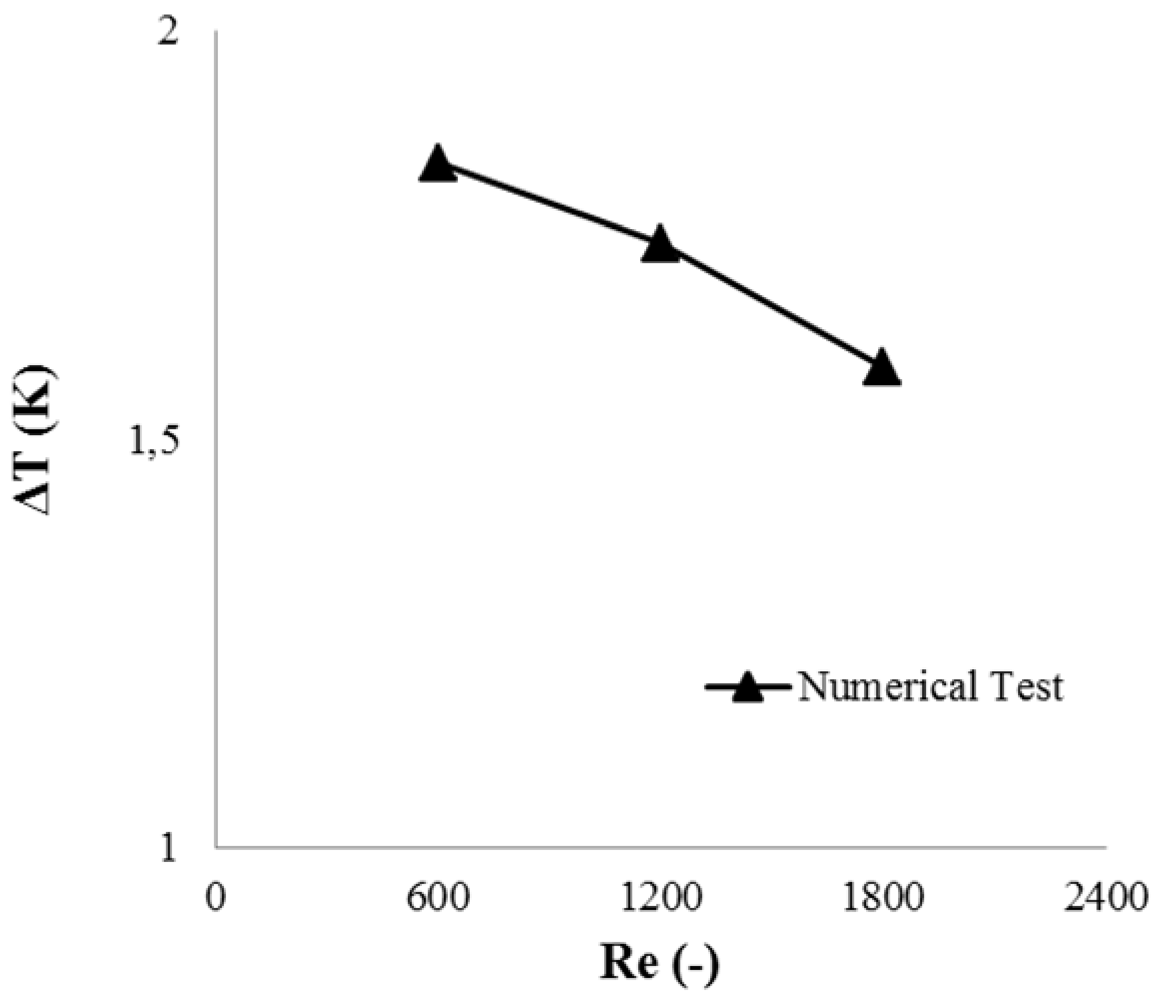

Figure 6

Comparison of maximum temperatures obtained by changing Reynolds numbers (pure water).

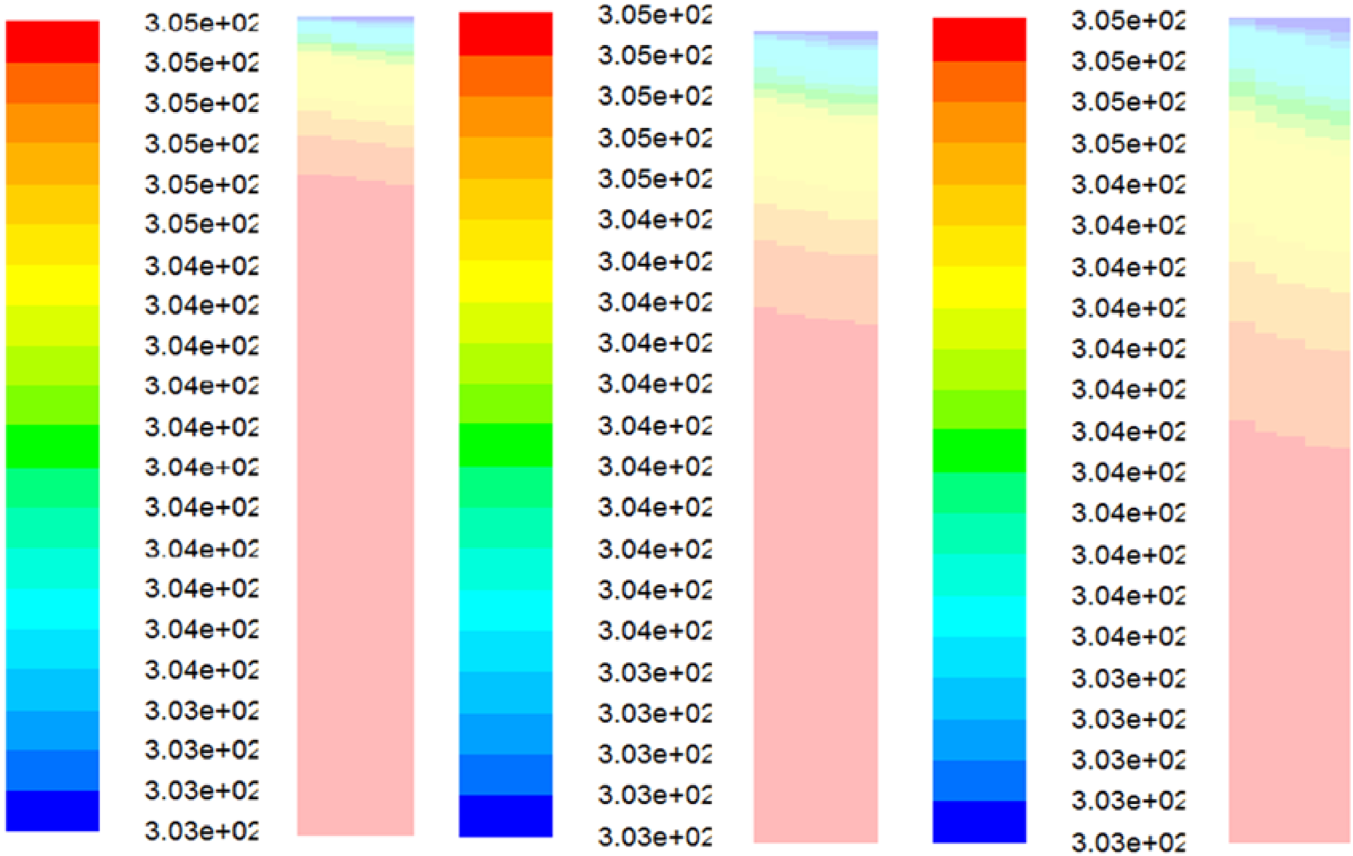

Figure 7

Comparison of the temperature contour obtained numerically for pure water with Re=600, 1200 and 1800, respectively.

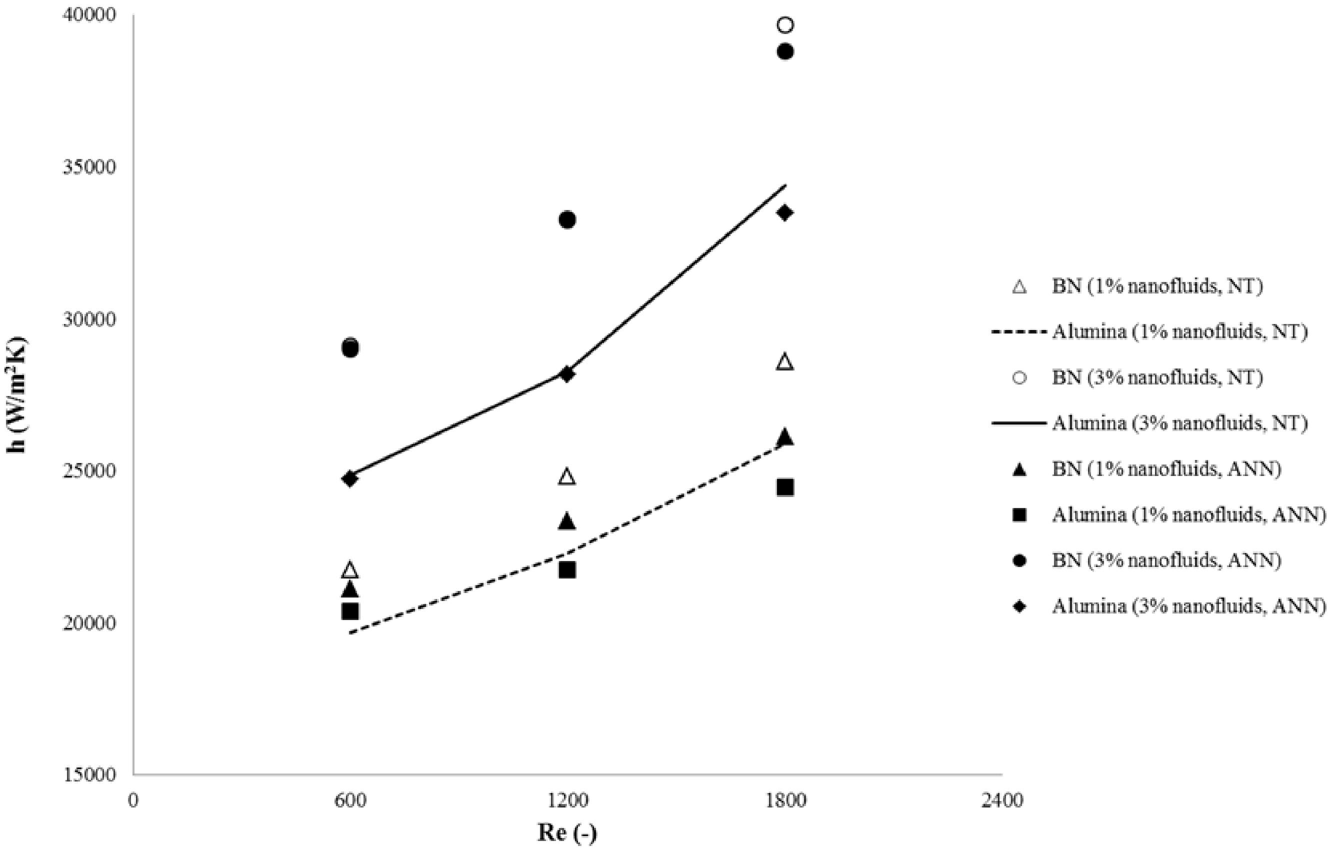

Figure 8

Comparison of the heat transfer coefficients values for different Reynolds numbers obtained by numerical tests (NT) and artificial neural network (ANN).

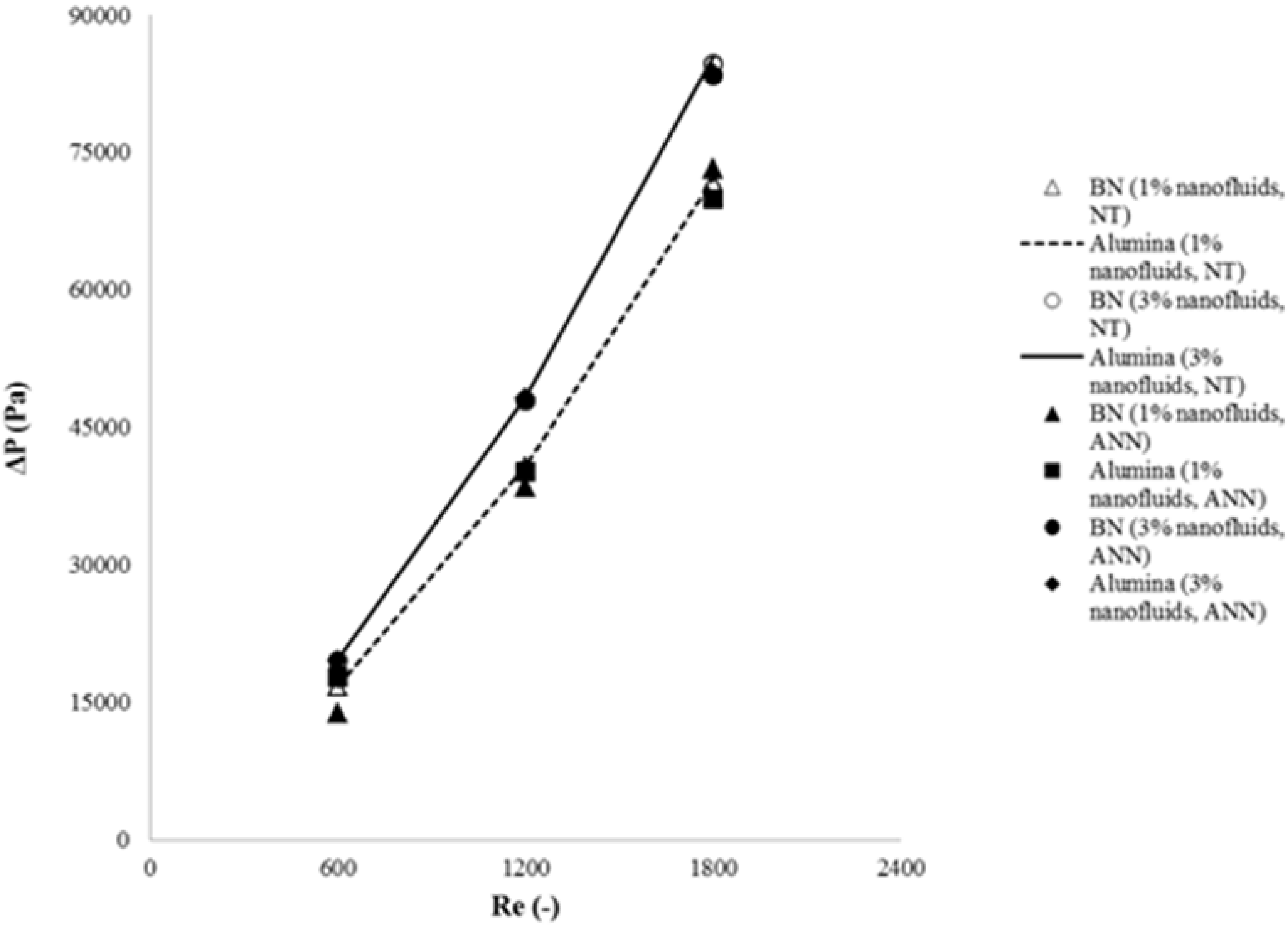

Figure 9

Comparison of the pressure drop values for different Reynolds numbers obtained by numerical tests (NT) and artificial neural network (ANN).

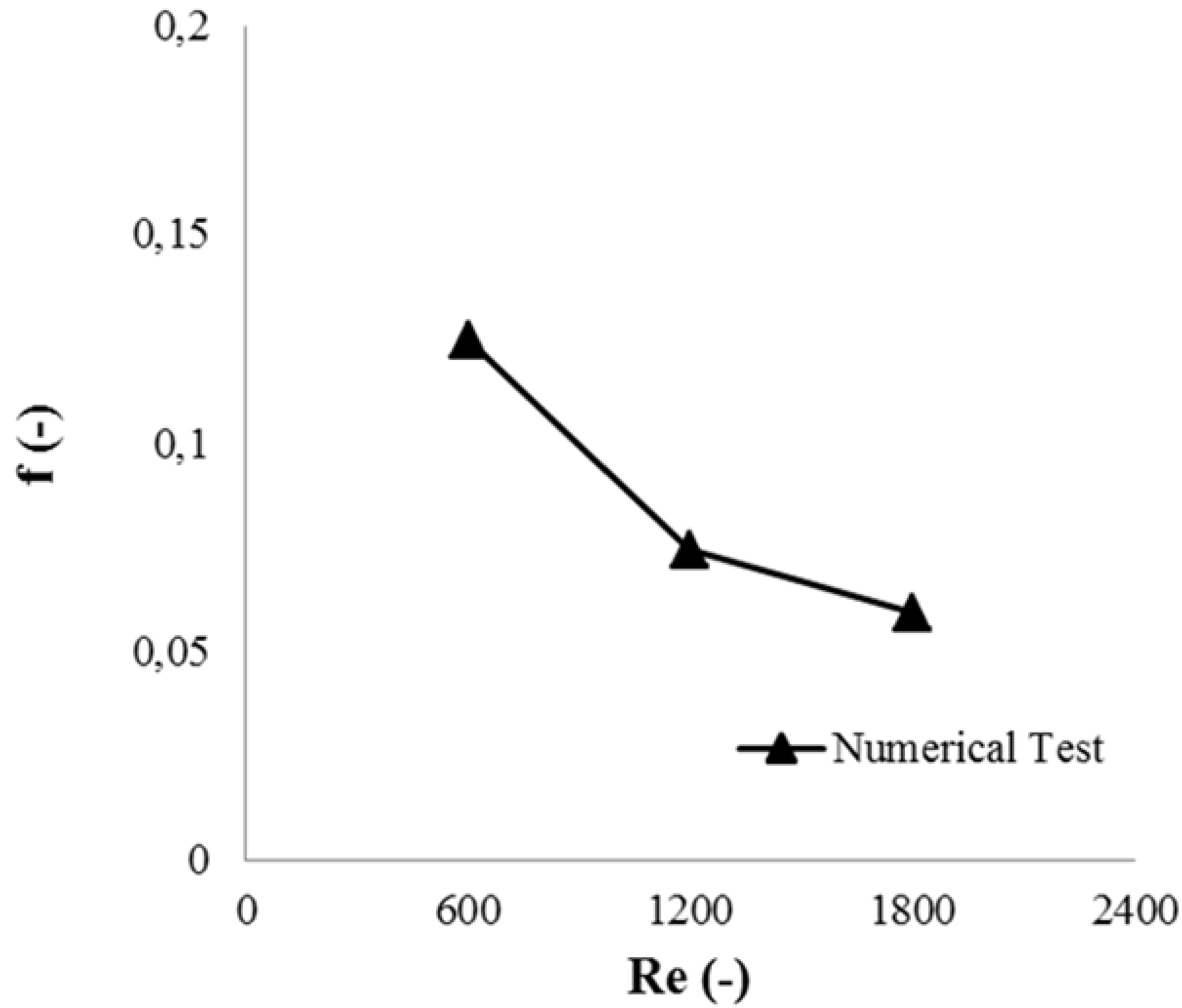

Figure 10

Comparison of friction factor values obtained by changing Reynolds numbers (pure water).