Enhancing the Thermal Efficiency of Gas Pressure Reduction Stations (CGS) Heaters Using the Twisted Tapes (Case study: Iran Golestan Qaleh-Jiq Station)

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ABSTRACT: *In this study, Twisted Tape has been investigated to increase the heat transfer in the heaters of the pressure reducing station with a capacity of 1,000 m^3 per hour (Golestan Qaleh-Jiq Station). The simulation was performed using Computational Fluid Dynamics (CFD). Simulation results were validated with the data collected from the station, and the simulation results were in good agreement with the data collected from the pressure-reducing station of Qaleh-Jiq, and the deviation from the experimental results was ± 0.1%. Then, three twist ratios of 0.5, 0.25, and 0.167 were considered to study its effect. Changes in speed, temperature, and pressure were analyzed. By inserting Twisted Tape into simple pipes, the length of the coil pipe and the energy consumption of the heaters were reduced by an average of 38% and 22%. This study shows that the efficiency of twisted tapes in the tubes with the highest twist ratio of 0.167 can have the highest efficiency and energy savings.*

KEYWORDS: *Heater; Pressure reducing station; Increasing heat transfer; Twisted tape.*

INTRODUCTION

The consumption of natural gas in the world is rising sharply. Since Iran is one of the first largest consumers among Eurasia & European countries, reduction of natural gas consumption is crucial and hence should be taken into account from production step to end consumers.

Once extracted, the natural gas is transferred to refinery units followed by sweetening and then transmitted to consumption centers through transmission pipelines. According to the long trip of natural gas from gas refineries to consumption points, the gas is injected into the transmission lines with high pressure (i.e. 1050 psig). Gas pressure reduction stations (city gate stations or CGSs) are mostly located near the consumption points such as the entrance of cities to reduce the gas pressure from the transmitting pressure to permissible one (i.e. 250 psig) while entering the cities and Town Boarder Stations (TBSs). In CGSs, the gas pressure reduction is done mostly by regulators within two stages. In the first stage, gas pressure is decreased from 1050 psig to 400 psig, and on the second one, it decreases from 400 psig to 250 psig. This process thermodynamically follows the Joule – Thompson (JT) effect where the pressure reduction occurs in constant

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enthalpy (well-known as an adiabatic process). According to JT effect, the pressure reduction through an adiabatic process could result in a consequent temperature decrease as well. Hence, to prevent the freezing process or hydrate formation, the gas flow should be pre-heated before any pressure regulation to reach a temperature beyond the hydrate formation temperature. To do so, heaters with atmospheric burners are used which play a vital role in the effective performance of CGSs.

Although CGS preheaters equipped with atmospheric burners are mostly used all around the world, however, they have their own advantages and disadvantages. While the most important advantages of these apparatuses are low operational costs and simple application, their disadvantages could be summarized as large size, the requirement to storing a high volume of water, low thermal conductivity (k) of heat transfer fluid (mostly water with k=0.6 W/m.°C), low heat transfer coefficient, and high energy consumption.

As mentioned before, pre-heaters need energy for heating the interfacial heat transfer fluid, a mixture of water and glycol. This energy is provided by burning natural gas. Therefore any action for reduction of gas consumption in pre-heaters could lead to energy saving and hence lower air pollution. According to the National Iranian Gas Company (NIGC) in 2016, about 181 billion cubic meters of natural gas were consumed in Iran with an overall heating value of around 8600 kcal per cubic meter. For preheating such an amount of natural gas (with available composition), around 370 million cubic meters of gas were consumed in preheaters of Iranian CGSs in 2016. Consequently, 10% reduction in natural gas consumption in preheaters could lead to an energy-saving of about 37 million cubic meters in a year. For this purpose, different studies have been carried out using numerous energy-saving procedures, and some newly issued researches are presented in the following section.

History

Azizi et al. (2014) carried out a study on the preheating of inlet gas to the heater where it was found that gas preheating increased 11% the heater efficiency with an economic efficiency of about 25% [1]. *Farzaneh-Gord et al.,* (2014) conducted the energy analysis and exergy in a gas pressure reduction station of which the heater is equipped with solar and control systems [2]. *Ashouri et al.,* (2014) investigated the effect of minimum inlet temperature to the regulators of CGS on the energy consumed by the heaters. Results showed that heating the gas to the minimum required temperature to prevent the hydration phenomenon leads to the equivalent energy storage of 43% [3]. *Farzaneh-Gord et al.,* (2015) investigated the effect of applying the geothermal heaters in gas pressure reduction stations on the reduction of fuel consumption.[4] *Arabkoohsar et al.,* (2015) presented a new design for CGSs by applying the turboexpander and solar system [5]. *Zabihi et al.,* (2015) examined the impact of outlet temperature control of the second regulator in the station on the heater fuel consumption [6]. *Ebrahimnia-Bajestan et al.,* (2016) dealt with the numerical and empirical investigation of heat transfer characteristics of nanofluids in solar exchangers [7]. *Farzaneh-Gord et al.,* (2016) investigated the use of ground dual heat pumps in CGS and its impact on energy consumption, economy, and CO_2 emissions [8]. *Farzaneh-gord et al.,* (2016) defined a technical criterion for economic feasibility to use the Combined Heat and Power (CHP) technology in CGSs [9]. *Arabkoohsar et al.,* (2016) investigated the minimization of energy consumption in a new combined power plant using the photovoltaic system and discharged tubes system of a solar thermal collector [10]. *Salari et al.,* (2017) examined the increased heat transfer and decreased energy consumption in CGSs [11]. They (2017) also investigated the exacerbation of heat transfer in tubes of CGS heaters using the spiral springs [12]. *Olfati et al.,* (2018) studied the energy and exergy in CGSs in four seasons [13]. *Borelli et al.* (2018) investigating the energy recovery from the natural gas pressure reduction stations applying the low-temperature heat sources [14]. *Rahmati et al.,* (2018) studied empirically the impact of using the multi-walled carbon nanotubes in heater bath ethylene glycol-water fluid in CGSs [15]. *Khosravi et al.,* (2019) examined the improved thermal efficiency in heaters using the baffles. In this study, it became clear that thermal efficiency increased up to 20%, and heater size with similar thermal load decreases by using the baffles; in other words, the fuel consumption of the heater would reduce [16]. *Tan et al*., (2013) conducted the 3D numerical simulation for heat transfer in the shell as well as the impact of pressure drop of twisted elliptical tubes in heat exchangers [17]. *Pozrikidis* (2015) studied the flow through a twisted tube with a square cross-section and elliptical twists under the Stokes current

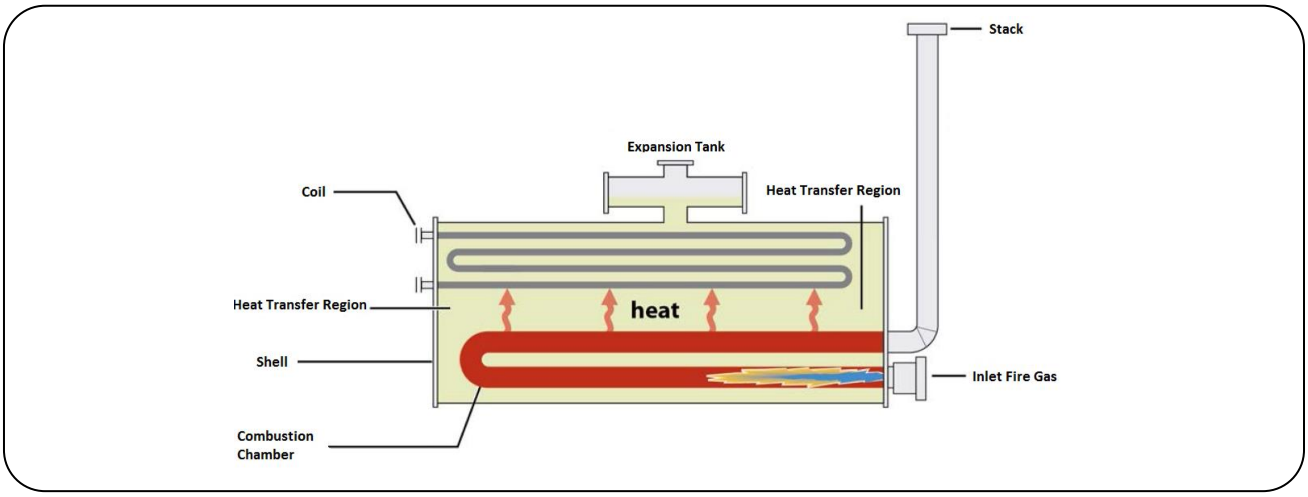

Fig. 11: A scheme of preheater.

conditions [18]. *Bhadouriya et al.,* (2015) studied empirically the properties of heat transfer and friction factor of air current inside the squared tube through 3D numerical simulations [19]. *Bhadouriya et al.,* (2015) investigated the properties of heat transfer and friction factor of air current inside an annulus by an internal twisted tube with a squared cross-section and an external circular tube for a Reynolds limit of 60-400 [20]. *Tang et al.,* (2015) examined empirically and numerically the heat transfer and fluid transfer in twisted spiral tubes [21]. *Khoshvaght et al.,* (2015) studied the forced convection in twisted mini-channels with various cross-sectional shapes from a numerical point of view [22]. *Khoshvaght et al.,* (2016) examined the impact of nano-fluid Al_2O_3/H_2O on the efficiency of twisted mini-channels [23]. *Khoshvaght et al.,* (2016) proposed a new design for squared twisted channels. Experimental results showed that the high-low arrangement has the most impact [24]. *Eiamsa-ard et al.,* (2016) investigated the impact of a triple twisted tube combined with twisted triple tapes in increased heat transfer [25]. *Hong et al.,* (2016) conducted an empirical study on heat transfer and properties of flow in spiral tubes with large and small twisted tapes [26]. *Cheng et al.,* (2017) analyzed the heat transfer and flow resistance in elliptical twisted tubes with low Reynolds numbers [27]. *Feizabadi et al.,* (2018) investigated numerically the flow of nano-fluids Al_2O_3/H_2O among the twisted tubes and their conformance with empirical results [28]. *Nematollahzadeh et al.,* (2020) studied analytical and numerical solutions for convective heat transfer in spherical extended surfaces with regular singular [29].

Fig. 2: Indirect heat exchanger (preheater).

Details of studied samples

Currently, the gas heating process in gas pressure reduction stations is conducted using indirect heat exchangers (preheaters) with atmospheric burners. A scheme of such preheaters, or so-called heaters, is shown in Fig. 1 [30].

In this study, preheater (heater) of Qaleh-Jiq gas pressure reduction station, Golestan Province, with a rated capacity of 1000 m^3/h with the minimum pressure of 1000 kPa and temperature of 288.15 K was examined as shown in Fig. 2. As it is observed in Fig. 1, this heater contains a cylindrical bath, U-shaped combustion chamber, gas flow coils, expansion tank, and a stack. The aim of designing a fire chamber is the fast transfer of heat released from the fuel to the water bath. The flow coil is also designed to transfer safely the process fluid (i.e. natural gas) and transmit the required heat from the water bath to the process flows.

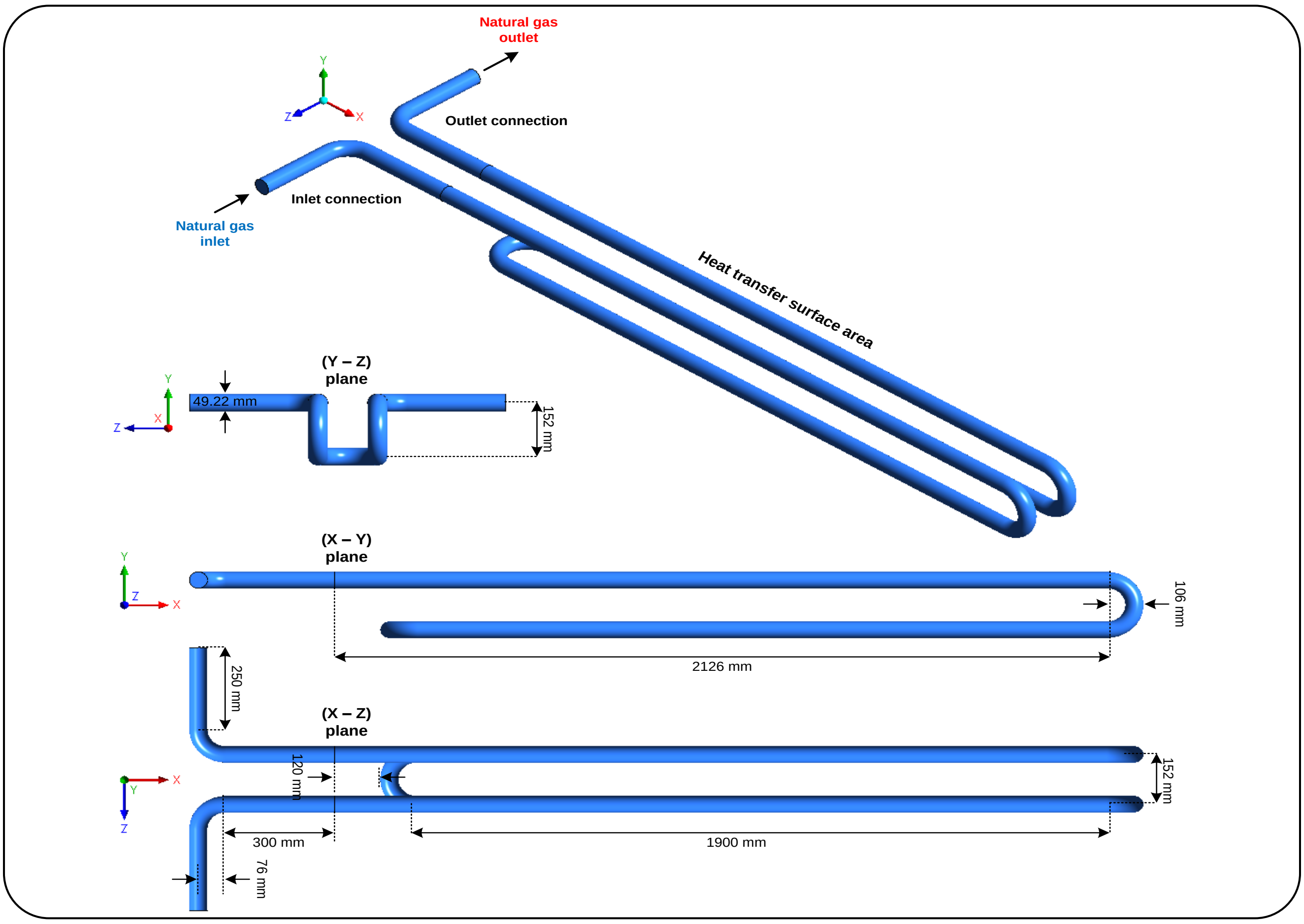

Fig. 3: Dimension characteristic of the simulated heater.

The expansion tank is responsible for collecting the extra water volume during the preheating procedure.

Numerical solution and simulation

Initially, the preheater in Qaleh-Jiq station was simulated by using the Computational Fluid Dynamics (CFD), and to validate, the simulation results were compared with the information recorded from the same preheater. In this simulation, the turbulent gas flow is considered to be stable and the simulation was made in 3D medium. The gas fluid was taken as single-phase and Newtonian. Radiation and natural heat transfer mechanisms were ignored. By defining the boundary conditions, the finite volume method was used for numerical solutions. Characteristics of simulated heater are given in Table 1 and Fig. 3. In addition, Table 2 summarizes the thermo-physical properties of methane.

As already mentioned, available data associated with the heater of Qaleh-Jiq gas pressure reduction station

Table 1: Information of simulated heater.

Capacity	1000 m^3/hr
diameter of coil	2 inch
Area of coil	1.6 m^2
Thickness of coil	5.54 mm
Inlet gas temperature	10ºC

with a capacity of 1000 m^3/h in Golestan Province was used in this research. Recorded information of outlet temperature and inlet gas pressure into the station were used daily in the one-month interval during the 21 March – 20 April 2017 as represented in Figs. 4 & 5. As a matter of fact, since the transmission pipelines are buried underground before reaching the City Gate Stations (CGSs), the temperature of natural gas entering the gas, the coil is almost equal to the ground temperature (i.e. around 283.15 K). According to gas-phase correlations, the outlet temperature of the natural gas where no natural gas hydrates are formed depends

Table 2: Thermophysical characteristics of methane.

Property	Definition
1. Heat capacity	cp/R = a1 + a2T + a3T2 + a4T3 + a5T4 a1 = 5.14987613, a2 = –1.36709788 e-2 K-1, a3 = 4.918005599 e-5 K-2, a4 = –4.84743026 e-8 K-3, a5 = 1.66693956 e-11 K-4
2. Dynamic viscosity	μ = μ0 (T/T0)3/2 (T0+S/T+S) T0 = 273.15 K, S = 197.8 K, μ0 = 1.172592 e-5 Pa.s
3. Thermal conductivity	k = k0 (T/T0)3/2 (T0+S/T+S) T0 = 273.15 K, S = 197.8 K, k0 = 0.0362914 W/m.K

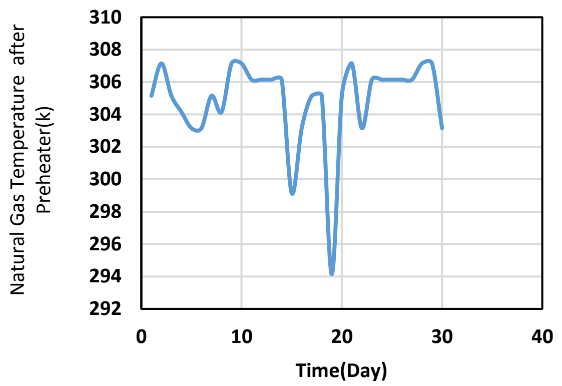

Fig. 4: Changes in Natural gas temperature after water bath heater with change in date.

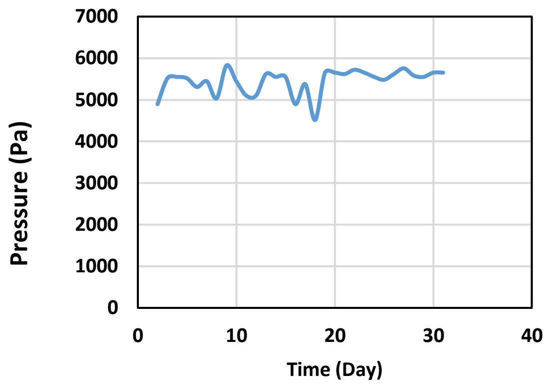

Fig. 5: Changes in Natural gas inlet pressure with change in date.

on the inlet pressure. Since in the real situation, the inlet pressure of the natural gas is around 5447 kPa (790 psig), the outlet temperature of the natural gas should be in the range of 303.15–313.15 K.

In the first stage of simulation, a number of meshes was changed to ensure the accuracy of results. In this research, the number of meshes was changed from 1 to 7.5 million during 10 stages and the obtained results are shown in Table 3 and Fig. 6. As could be seen from Table 3, one can conclude that number of meshes equal to 3,200,000 is appropriate to continue the work.

Once the independence of meshes on the outlet temperature was confirmed, the model of turbulency was evaluated to choose the equation with the best answers around the turbulence type of the flow. For this purpose, the performance of kε and kω equations as well as RNG Standard, Realizable, SST, and BSL models were assessed. Table (4) and Figs. 7 & 8 represent the performance of the abovementioned equations and models in this study. As could be concluded, that kε model and the realizable method had the best answers to simulation.

The Boundary Conditions (BC) in the simulation step were fully developed velocity and constant temperature of the coil wall. It is worth mentioning that, the second BC is defined since the temperature of the water bath adjacent to the coil is controlled by means of a control valve adjusting the fuel flow into the burner. In addition, the inlet gas temperature was assumed 283.15 K according to real data.

With regards to the best-identified turbulence equation for simulation, their mathematical equations are as below:

Continuity equation:

$$\frac{\partial}{\partial xi}(pui) = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial}{\partial x_i}\left(pu_i u_j\right) = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i}(\mu + \mu_t)\left(\frac{\partial ui}{\partial x_j} + \frac{\partial uj}{\partial x_i}\right) \tag{2}$$

Table 3: Information of independence from mesh.

Test No.	Number of grids	Outlet temperature (K or °C)	Deviation (%)
1	1051440	307.6316 or 34.4816	–
2	1422720	307.8568 or 34.7068	0.6531
3	1778400	307.9655 or 34.8155	0.3131
4	2134080	308.0266 or 34.8766	0.1755
5	2489760	308.0643 or 34.9143	0.1081
6	2803840	308.0953 or 34.9453	0.0887
7	3201120	308.1211 or 34.9711	0.0738
8	3504800	308.1274 or 34.9774	0.0180
9	3912480	308.1308 or 34.9808	0.0097
10	7680560	308.1310 or 34.9810	0.0006

Table 4: Summary of results of turbulency model.

Test No.	Turbulent model	Number of iterations	The predicted value of outlet temperature (K)	Deviation with real value (%)
1	Standard k–ε	10250	308.1103	2.824
2	RNG k–ε	8100	308.3763	3.606
3	Realizable k–ε	9000	307.9121	1.065
4	Standard k–ω	8900	308.2112	3.121
5	SST k–ω	7700	308.2482	3.230
6	BSL k–ω	8700	308.2303	3.177

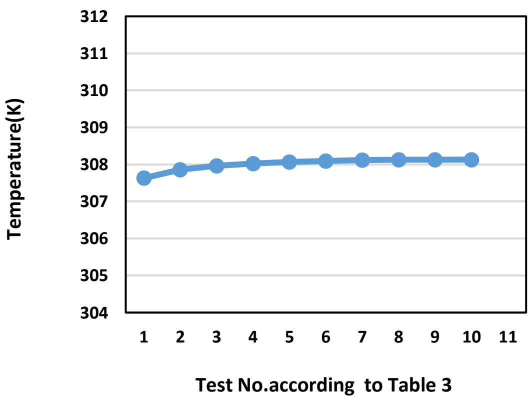

Fig. 6: Changes in outlet temperature with change in mesh number.

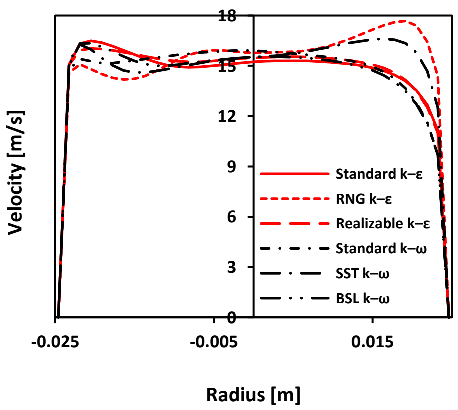

Fig. 7: Changes in outlet speed with changes in turbulency equation.

Energy equation:

$$\frac{\partial}{\partial x_i}(u_i T) = -\frac{\partial}{\partial x_i}\left[\frac{\mu}{pr} + \frac{\mu_t}{pr}\left(\frac{\partial T}{\partial x_i}\right)\right] \tag{3}$$

Where, ρ is the density of natural gas, u is speed, p is pressure, μ is the dynamic viscosity, μt is the turbulence viscosity, T is temperature and Pr is the Prandtl number.

Kinetic energy equations k and ε are as follows:

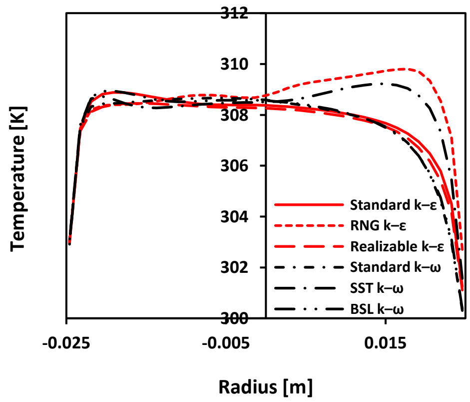

Fig. 8: Changes in outlet temperature with changes in turbulency equation on the outlet of the heater tube.

$$\frac{\partial}{\partial x_i}\left(\rho k u_j\right)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+\Gamma-\rho\varepsilon \tag{4}$$

$$\frac{\partial}{\partial x_i}\left(\rho\varepsilon u_j\right)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+ \tag{5}$$

$$C_1\Gamma\varepsilon-C_2\frac{\varepsilon^2}{k+\sqrt{\nu\varepsilon}}$$

$$\Gamma=-u_iu_j\frac{\partial u_i}{\partial u_j}=\frac{\mu_t}{\rho}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial uj}{\partial x_i}\right)\frac{\partial ui}{\partial x_j} \tag{6}$$

$$C_1=\max\left[0.43\frac{\mu_t}{\mu_t+5}\right]\quad,\quad C_2=1.0 \tag{7}$$

$$\sigma_\varepsilon=1.2\quad,\quad\sigma_k=1.0\quad,\quad\mu_t=\rho C_\mu\frac{k^2}{\varepsilon} \tag{8}$$

In this stage, since we have found the highest rate of mesh and the best choice for turbulence, we go to the next stage, i.e. simulation of coil tubes equipped with twisted tapes.

The tube cross-section is circular and the ratio of tape twist is also taken 0.5, 0.25, و and 0.167. In the first stage, the tape was simulated with two steps, in the second one with four steps, and in the third stage with six steps. All these simulations are shown in Fig. 9.

RESULTS AND DISCUSSION

Fig. 10 shows changing of speed within the simple tube as well as twisted tapes with two, four, and six steps. Maximum speed in the simple tube is in the range of 16-18 m/s where using more number steps could increase the speed. As it is expected, the speed in walls is zero, and the more we get away the speed increases. But in all states, the speed does not exceed 20 m/s which is known as the permissible speed limit in gas pipelines. In other words, in case of any changes in tube shape from simple to twisted tapes which form spiral flow, heat transfer was increased. As the gas passes through the tubes equipped to twisted tubes, the uniform path of gas flow changes, and the transverse and ordinary flow are exacerbated leading to a better mixture of fluid. While flow lines are steady in simple tubes, in tubes with twisted tapes, the flow lines are rotated and take more twisted form Therefore, in this circumstance the thermal layer regime does not remain along the walls anymore. This turbulency results in the distribution and dissemination of the boundary layers. It is fully evident that once the number of steps in twisted tapes increases, the turbulency also increases. Consequently, the third model (I.e. six steps) has the most impact over the first and second models and simple tubes as well.

Figs. 11 & 12, represent the trend of changes in temperature both in simple tubes and tubes equipped to twisted tapes for all different types of the tube considered in this research. As could be seen, more twisting the tapes would increase the gas temperature more rapidly. In other words, the desired temperature, i.e. 308K would be achieved at a shorter distance from the gas inlet location. In the tape with two twists, at the beginning of the third path, the gas temperature reaches 308 K (the desired temperature based on the data collected from Qaleh-Jiq station heater), while this temperature is obtained in the tape with four twists at the end of the second path and with six twists at the middle of the second path. Concerning these temperatures, one can conclude that the remaining length of the tube is surplus and there is no need for extra length to achieve the desired temperature. In fact, one can reduce the heat volume by decreasing the length of the tube, and also the energy can be saved. In such a case, the path of gas motion changes permanently along the tube; as a result, more turbulency is created among the various flow layers with normal status and such turbulency in layers increases the temperature along the shorter path.

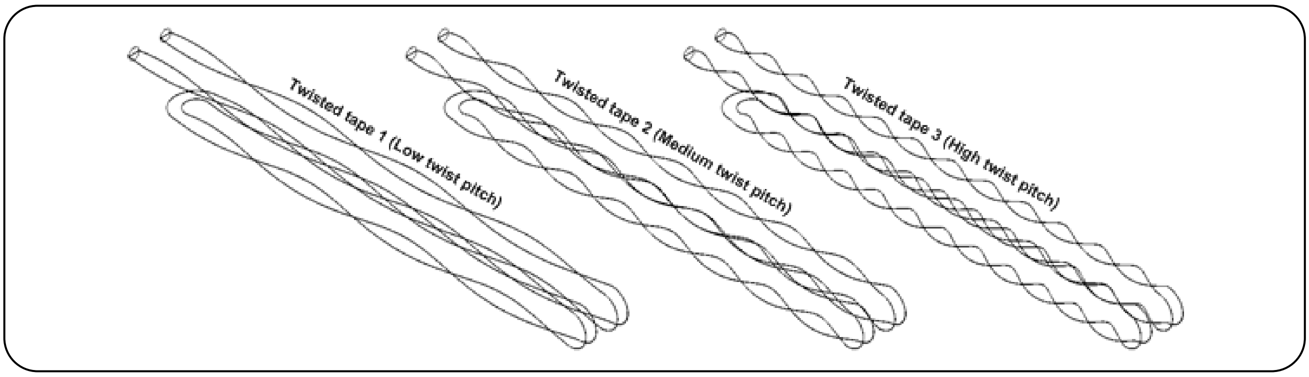

Fig. 9: Tube simulation and twisted tape with various steps.

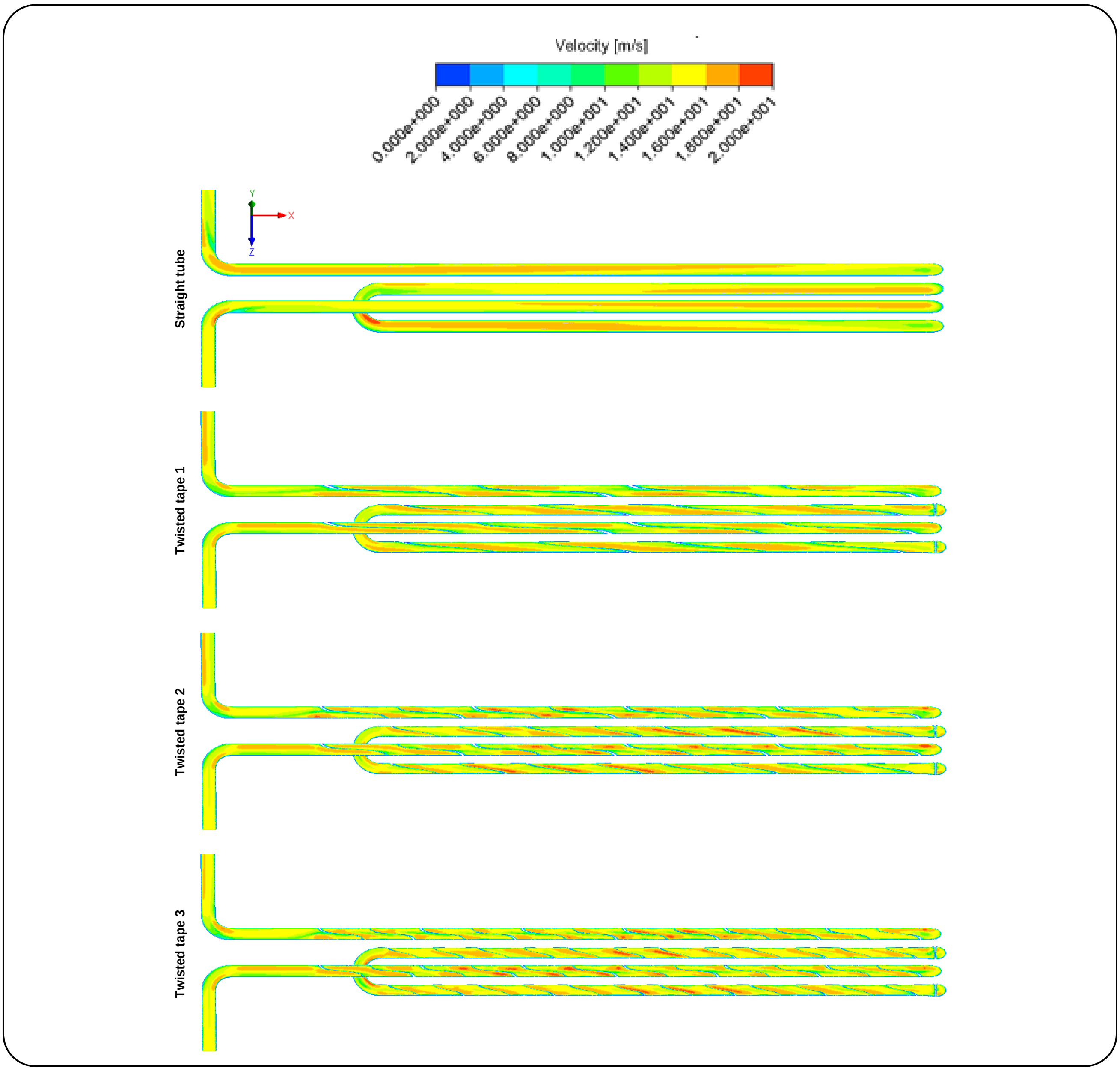

Fig. 10: Comparing the changes in speed counters in a simple tube and twisted tape with different steps.

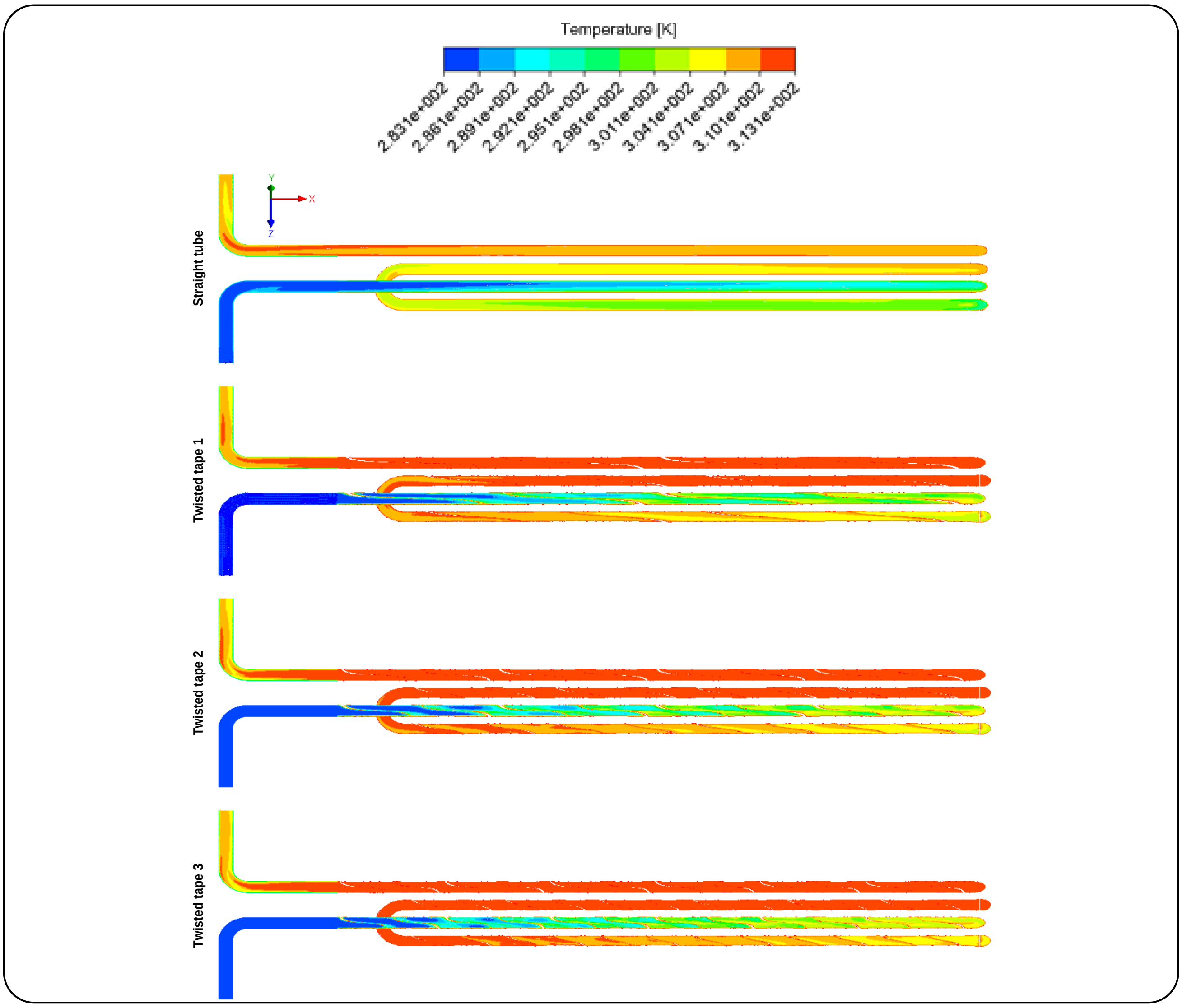

Fig. 12: Comparing the changes in temperature counters in a simple tube and twisted tape with different steps.

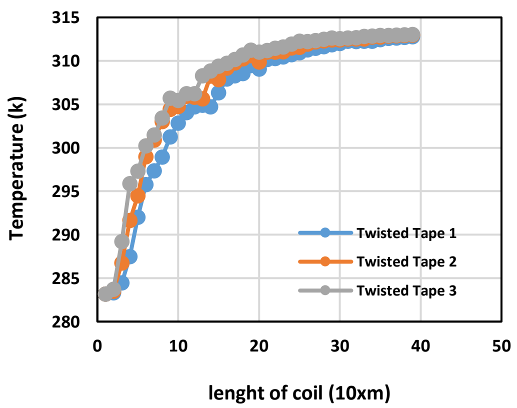

Fig. 12: Changes in outlet temperature with change in twisted tape with different steps.

By a simple calculation, it can be found out that in the first, second, and third models, 17%, 45%, and 57% of the coil tubes length are surplus, respectively. As the length of coil tubes decreases, the volume of the heater tank decreases. By doing so, need to energy for heating the water inside the tank is also reduced. Calculating the heat transfer in simple state and in models 1, 2, and 3, and their comparison shows that by applying such technique, there would be a decrease equal to 38% and 22% in length of coil tubes and energy consumption, respectively. To calculate the heat needed for heating the gas passing through the heater, Equations (9) to (14) were used. In these equations, the convection heat transfer coefficient, Reynolds number, and thermal resistance are initially calculated followed

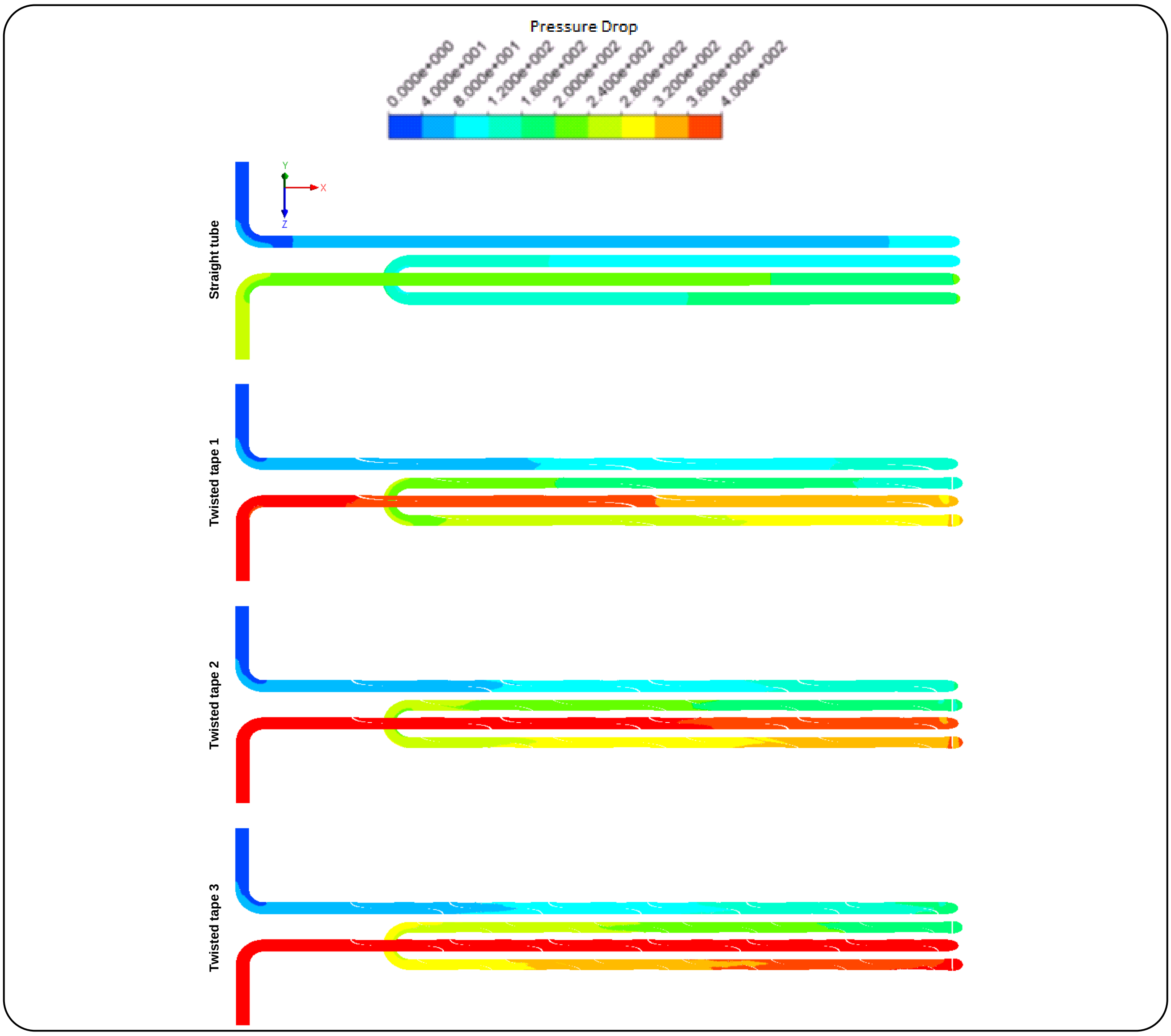

Fig. 13: Comparing the changes in pressure drop counters in simple tubes and twisted tape with different steps.

by calculation of mass transfer rate through the density and the average gas speed. Finally, using Equations (13) and (14), the required heat and then the tube length would be calculated. Calculation of heat transfer in simple state and models 1, 2, and 3 and their comparison indicates that we will have on average a 22% reduction in energy consumption.

$$h = \frac{Nuk}{D} \tag{9}$$

$$Re = \frac{\rho VmeanD}{\mu} \tag{10}$$

$$R = \frac{1}{Ah} \tag{11}$$

$$m(gas) = \rho(gas)VmeanA \tag{12}$$

$$Q(coil) = m(gas)Cp(Tout - Tin) \tag{13}$$

$$L(coil) = \frac{Q(coil)R}{LMTD} \tag{14}$$

Where, h is the convection heat transfer coefficient (W/m^2.°C) , Nu is the Nusselt number, k is the conduction heat transfer coefficient (W/m.°C), D is the coil diameter (m), Re is the Reynolds number, ρ is the density (kg/m^3),

V_{mean} is the mean gas speed (m/s), μ is viscosity (cp), R is the thermal resistance (°C/W), m(gas) is the gas mass transfer rate (kg/s), Q(coil) is the heat transfer from the coil (kW), Cp is the thermal capacity (kJ/kg.°C), T is the temperature (°C), L is the coil length (m), and $LMTD$ is the logarithmic mean temperature difference (°C).

In Fig. 13, changes in pressure drop are shown. As was expected, once the number of tape twists increases, the pressure drop also increases. This pressure drop is desired in the preheater system and there is no need to compensate it after passing coils because after the gas passes through the preheater, it enters the throttling valve in which the pressure is reduced. So, this pressure drop is helpful for the next process of the system and more drops will be more desirable.

CONCLUSIONS

This study investigated the hydrothermal efficiency of the preheater of a pressure reduction station with a capacity of 1000 m^3/h. According to the obtained results, it was demonstrated that applying the tubes with twisted tapes instead of typical simple tubes used in these preheaters, could increase the preheater thermal efficiency and reduce the fuel gas consumption. To examine this matter, variables of speed, temperature, and pressure were studied by numerical methods. The equations were solved with the finite volume method by a computer with 16000 MHz RAM and 32 GB xenon hard. Real data from Qaleh-Jiq pressure reduction stations, Golestan Province, were collected for 30 consecutive days. The simulation results had a signed agreement with real data with an approximation error of ±1%. Counters of temperature, speed, and pressure in simple and twisted states were compared. Tubes with twisted tapes had better temperature efficiency over the simple tubes. In general, any changes in the hydrothermal efficiency of the preheater depend on the tapes twist. The thermal efficiency of coil tubes increases with an increase in twist ratio. Outlet temperature from the coil is an important and effective parameter. In fact, by replacing the twisted tapes inside the sample tubes, the coil tube length has reduced 38% on average. In this case, the length of coil tubes and the preheater size have been decreased meaning the reduction of heater volume. Once the heater volume is decreased, less energy is needed to heat the water. By 38% reduction in length of heater tubes, the heaters' energy was saved around 22%.

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