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Use of Helical Coil Pipes for Depressurization in a Supercritical Water Oxidation (SCWO) Pilot Plant: Experimental Results & Simulation

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The use of backpressure regulator valves in SCWO at laboratory scale is highly extended, but the use of that valve is not suitable when applying this technology with high flow rates at industrial scale. The aim of this work is to present the use of helical coil pipes to achieve the depressurization step based on the pressure drop of a fluid that circulates for a pipe of great length and small diameter. To design it, several correlations of friction factors were studied and simulated with Engineering Equation Solver (EES) Software. Finally, the depressurization system installed in the SCWO pilot plant located at University of Cádiz, is composed of three series legs of helical coil pipes.

In order to compare simulated and experimental data, a set of experiments were carried out at pilot plant with air and water mixture feeds. The working pressure is approximately 250 bar and the flow rates were 10 l/h for water stream and 80 g/min for air stream. Experimental results obtained are compared with the simulation carried out with friction factor correlations appearing in the literature. The best fit is achieved adding a new parameter proposed in this work that takes into account interaction between gas and liquid phases.

1. Introduction

Supercritical water oxidation (SCWO) is a high temperature and pressure process whose operational conditions are above the critical point of the pure water (T_c=374ºC and P_c=221 bar), an excellent reaction medium due to its special properties, being possible a single reaction phase (no mass transfer limitations), very high reaction rates (removal efficiencies >99.99) and non-harmful products, allowing the effective treatment of industrial wastewaters. A typical SCWO process involves several steps that are needed to work at high pressure and temperature, including pressurization, heating, reaction, cooling, depressurization and phase separation. Most works are performed at laboratory and pilot plant scale where the depressurization step is easily carried out by a backpressure regulator valve. However, the use of this valve is not suitable when this technology is applied with high flow rates at industrial scale, mainly in the presence of particles that may enhance the problems of valve erosion. In this sense, the study and

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implementation of alternative depressurization systems for the SCWO process is highly necessary. Our proposal is to use helical coil pipes in order to reduce the pilot plant pressure based on the pressure drop trough a fluid that circulates for a pipe of great length and small diameter. Typical values of pressure drop of fluids circulating through these types of system have been widely studied in the industrial process.

Helical coil pipes have been used in a wide variety of applications due to their many practical advantages, such as compactness, easy manufacture and high efficiency in heat transfer. In this case, helical coil pipes have been used in the depressurization step of a SCWO pilot plant where the pressure drop necessary is around 240 bar.

Due to centrifugal forces the pressure drop in coil pipes is higher than pressure drop in the same length of straight pipes, because the presence of secondary flow dissipates kinetic energy, thus increasing the resistance to flow. Therefore, the transition from laminar to turbulent flow that is marked by the critical Reynolds number (Re_{cr}), in coil pipes is as high as 6.000 to 8.000 while in straight pipes Re_{cr} is approximately 2100.

Ito (1959) suggested a correlation to obtain the critical Reynolds number.

$$\mathrm{Re}_{cr} = 20000 \cdot \left(\frac{d}{D}\right)^{0.32} \tag{1}$$

Where d is the inner diameter of the pipe in m and D is the diameter of the coil in m.

The prediction of pressure drop in helical coil pipes is an essential step for the design of depressurization systems for SCWO. In this work, several correlations of friction factors have been studied and simulated with Engineering Equation Solver (EES) Software to determine the necessary length to reduce the pressure of the system from 250 to 5 bar.

For turbulent flow conditions, the friction factor in helical coil pipes (f_c) has been calculated using the correlations proposed by different authors; White (1932) developed the following correlation for smooth tubes under turbulent flow conditions, which is useful as a first approximation for the design of coiled tubes:

$$f_c = 0.08 \cdot \mathrm{Re}^{-0.25} + 0.012 \cdot \left(\frac{d}{D}\right)^{0.5} \qquad 15000 < \mathrm{Re} < 1 \cdot 10^5 \tag{2}$$

Ito (1959) suggested a theoretical equation in turbulent flow:

$$4 \cdot f_c \cdot \left(\frac{D}{d}\right)^{0.5} = 0.029 + 0.304 \cdot \left(\mathrm{Re}\left(\frac{d}{D}\right)^{2}\right)^{-0.25} \qquad 0.034 < \mathrm{Re}\left(\frac{d}{D}\right)^{2} < 300 \tag{3}$$

Gnielinski (1986) refined the above correlations and suggested the following equation to calculate the friction factor in turbulent flow:

$$f_c = 0.0791 \cdot \mathrm{Re}^{-0.25} + 0.0075 \cdot \left(\frac{d}{D}\right)^{0.5} \qquad \mathrm{Re}_{cr} < \mathrm{Re} < 1 \cdot 10^5 \tag{4}$$

Reynolds number depends on density and viscosity that are function of pressure, therefore, along helical coil pipes the Reynolds number changes due to decrease of the pressure with the length. In order to take into account these variations, the model has been built up with differential elements, each one with an initial and final pressure that varies until outlet pressure.

In order to compare simulated and experimental data, a set of experiments were carried out at pilot plant with air and water mixture feeds. Experimental results obtained are compared with the simulation carried out with friction factor correlations appearing in the literature.

2. Materials and Methods

Supercritical water oxidation experiments were conducted in a SCWO pilot plant. This plant was designed to treat up to 23 kg/h of aqueous wastes. The aqueous feed solution is pressurized up to 250 bar with a high pressure pump and the oxidant (air) is pressurized by a high pressure compressor. The effluent of the reactor is used to preheat both feed streams, so its temperature decreases from 550ºC to 200ºC.

A cooler is used to decrease the effluent temperature below 50ºC before reaching the depressurization system. Finally, the gas stream is separated from the liquid stream in the gas/liquid separator and later the composition is analyzed in a gas analyzer. More details of the system and procedure can be found in a previous work (García-Jarana et al, 2010). In the original pilot plant, the depressurization system was only formed by a backpressure regulator valve. In this work, a series of helical coil pipes have been installed in parallel with the backpressure regulator valve.

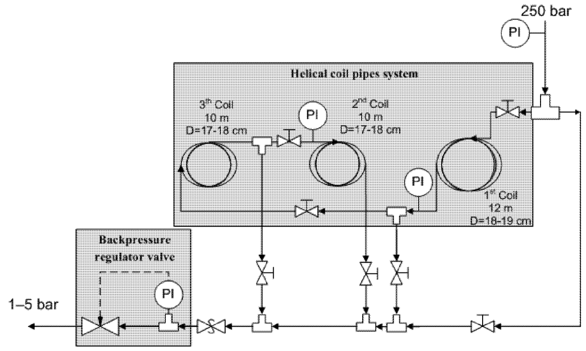

Figure 1: Schematic diagram of depressurization system.

A schematic diagram of the new depressurization system is shown in Figure 1. This configuration allows the effluent to circulate through each leg of helical coil pipes, either individually or in series, depending on the effluent flow rate and the requirements needed. Helical coil pipes are composed of three series legs of stainless steel (AISI 316 L) tube of 1.0795 mm inner diameter, each of them with different length and coil diameter, the first 12 m and 19 cm, respectively and second and third 10 m and 18 cm. With the designed system of valves and bypass, it is possible the circulation of the fluid through one, two or three legs of helical coil pipes depending on the necessary pressure drop. The inlet and outlet pressure of each helical coil pipe is monitored using pressure transmitters linked to a data acquisition system.

The assays were carried out in the pilot plant for steady isothermal flow of air and water, using two legs of helical coil pipes with a total length of 22 m. The initial pressure was 250 bar and the final pressure was monitored and recorded to calculate the pressure drop. The flow rates were 10 l/h for water stream and 80 g/min for air stream. The friction factor was calculated for different correlation knowing the pressure drop and mean velocity of the flow.

The software used to calculate the pressure drop for different correlation was Engineering Equation Solver (EES). The basic function provided by EES is the solution of a set of algebraic equations, including a data base for thermodynamic and transport properties of many substances.

3. Results and Discussion

As mentioned before, the feed stream that enters the depressurization system is composed by water and air, that is, it is a biphasic stream. However, the correlations used are defined for a single phase.

As first approximation, the pressure drop in helical coil pipes (Eq. 5) has been calculated using quoted correlations (Eq. 2, Eq. 3, Eq. 4) to determined frictions factors, assuming the mixture of air and water as a monophasic fluid with properties like density and viscosity evaluated through a mass average.

$$\Delta P_{av} = f_{c,av} \cdot \frac{L_c}{d} \cdot 2 \cdot \rho_{av} \cdot v_{av}^{\ 2} \tag{5}$$

Where ΔP_{av} is the average pressure drop in Pa, L_c is the length of helical coil pipe in m, $f_{c,av}$ is the average friction factor calculated with the correlations appearing in the literature (Eqs (2), (3) and (4)), d is the inner diameter of pipe in m, ρ_{av} is the average density in kg/m^3 and v_{av} is the average mean velocity of the flow in m/s. In the second approximation made, the pressure drop for each phase has been calculated individually, considering that each phase circulates through the free section of the pipe that it occupies in terms of its volumetric fraction. In this way, ΔP_p is the pressure drop for each phase, that is, ΔP_{air} or ΔP_{water} respectively, in Pa, f_{cp} is the friction factor for each phase calculated using inner diameter of pipe, ρ_p is the density for each phase in kg/m^3 and v_p is the mean velocity of the flow for each phase in m/s. Hence, the global pressure drop (ΔP_G) has been evaluated according to the following equation:

$$\Delta P_G = \Delta P_{air} \cdot X_{air} + \Delta P_{water} \cdot X_{water} \tag{6}$$

Where $\Delta P_{air/water}$ is the pressure drop and $X_{air/water}$ is the volumetric fraction, both for air and water respectively.

Experimental data were obtained take into account that the critical Reynolds number estimated with Eq. (1) gives a value close to 4.000. In this work, the Reynolds number ranged from 8.500 to 9.000, so all tests were carried out under turbulent flow. In assays performed at the pilot plant, the inlet pressure in helical coil pipes was 248 bar and the outlet pressure was 35 bar, therefore, the experimental pressure drop is 213 bar approximately.

Table 1: Pressure drop simulated with different correlation for the friction factor

Correlations	ΔP_{av} (bar)	ΔP_{air} (bar)	ΔP_{water} (bar)	ΔP_G (bar)
White, 1932 (Eq. 2)	101	87.98	149.2	118.8
Ito, 1959 (Eq. 3)	92.34	77.19	136.6	107.2
Gnielinski, 1986 (Eq. 4)	96.13	80.73	142.3	111.8

Table 1 summarizes results obtained with different friction factors simulated for air and water under turbulent flow conditions.

Based on the comparison of first (ΔP_{av}) and second (ΔP_G) approximations using quotes correlations with our experimental data, we found that the experimental pressure drop is always higher than predicted by the correlations in approximations (Figure 2). The cause of that difference may be due to the interactions between the gas and liquid phases that have not been taken into account in those estimations, since the pressure drop for each phase has been determined independently. In order to fit the experimental results, a new correlation is proposed in this work, based on Gnielinski correlation but adding a new parameter that accounts for the possible interactions between the gas and liquid phases by taking into account the volumetric fraction ratio for air and water.

$$f_c = 0.0791 \cdot \mathrm{Re}^{-0.25} + 0.0075 \cdot \left(\frac{d}{D}\right)^{0.5} + a \cdot \left(\frac{X_{air}}{X_{water}}\right)^{b} \tag{7}$$

Where $X_{air/water}$ is the volumetric fraction for air and water in m^3/s and a, b are constants that are determined making use of the experimental assays. Values are 0.001757 and 1.358 for a and b, respectively.

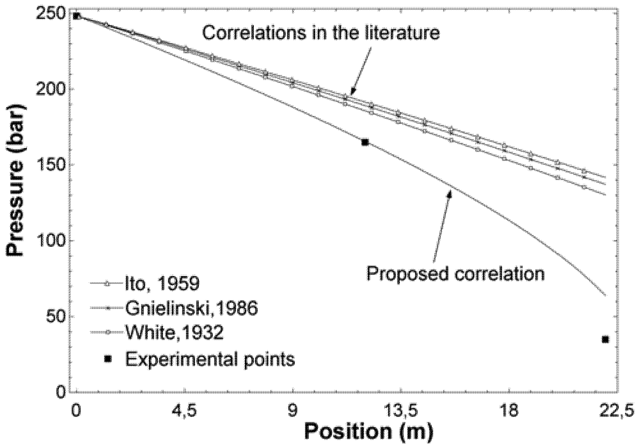

Figure 2: Pressure in helical coil pipes as function of position for different correlations.

Figure 2 depicts the pressure in helical coil pipe as a function of position for the different correlations used and experimental data obtained in assays. As can be seen, the correlation proposed fits the experimental results quite better than previous correlations, which do not take into account the interactions between the two phases circulating through the helical pipe.

4. Conclusions

Simulations carried out with friction factor correlations, appearing in the literature, have been employed in the design of helical coil pipes in order to implement an alternative depressurization system in SCWO pilot plant at University of Cádiz.

The assays carried out prove that is possible to use helical coil pipes, instead a back pressure regulator, to achieve the depressurization step in a SCWO pilot plant, assuring stable and controlled behavior of the system. Experimental data obtained for the pressure drop into the helical coil pipes is different to simulated results based on correlations appearing in the literature. In this way, a new correlation has been proposed to take into account the ratio of volumetric fraction for air and water, therefore, achieving a better fit between experimental results and simulated one.

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