Supporting Information

Effect of Steam Quality on Extra-Heavy Crude Oil Upgrading and Oil Recovery Assisted with PdO and NiO-Functionalized Al_2O_3 Nanoparticles

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S1. Steam injection

First, the system of interest for modeling was identified; it consists of a steam generator (part 6 of Fig. 2) and the porous medium (part 11 of Fig. 2). It was important to characterize the connection between these two devices since this is how energy losses can be caused and the steam change condition.

The energy losses through the connection system between the steam generator and the porous medium were calculated considering the system shown in Fig. S1.

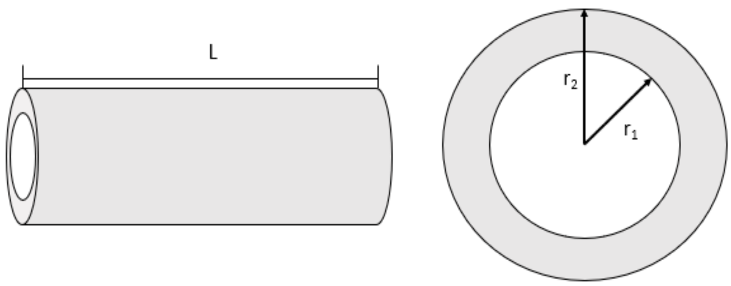

Fig. S1. System considered for the calculation of energy losses between the steam generator and the porous medium.

The energy losses were calculated considering the resistance to heat transfer through the transport system radially as shown in Eq. (S1):

$$Q_L = \frac{T_{in} - T_s}{\sum R} \tag{S1}$$

where, Q_L is the energy lost by the steam flowing through the pipe (W), T_{in} is the internal temperature of the steam, T_s is the surrounding temperature, and $\sum R$ is the sum of all the thermal resistances considered for the system (K·W-1).For the case analyzed, losses inside the tube due to convection processes are not considered since a phase change occurs. The heat transfer coefficients (h) calculated from Eq (S2) [34], which are between 40000 W·m-2·K-1and 50000 W·m-2·K-1. Commonly, this correlation is for high value of heat transfer coeffcients for representing the process, from there is possible to conclude that resistance to heat transfer can be neglected.

$$h = 2080\left(\frac{L}{\dot{m}}\right) \tag{S2}$$

where, L is the tube length (m) and $\dot{m}$ is the mass flow (kg s-1). Also, for obtaining the external convection coefficient was used the Eq. (S3) [34].

$$h_\infty = 1.31\left(\frac{T_s - T_\infty}{2r_2}\right)^{1/4} \tag{S3}$$

where, T_s and T_∞ are the temperatures at the tube surface and the environment temperature respectively. r_2 is the outer radio (m).

The resistances considered in the system are conduction through the material in which the steam circulates Eq. (S4) and convection to the surroundings (Eq. (S5)) [34].

$$R_{cond} = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi KL} \tag{S4}$$

$$R_{conv} = \frac{1}{h_\infty 2\pi r_2 L} \tag{S5}$$

where, R_{cond} and R_{conv} are the resistances by conduction and convection (K·W-1), respectively, r_2 and r_1 are the outer and inner radio (m), L is the length of the connection between the steam generator and the inlet to the porous medium (m), K is the thermal conductivity of the material (W·m-1·°C-1), and h_∞ is the coefficient of external convection (W·m-2·°C-1). Table S1 shows the parameters to calculate the energy losses.

Table S1. Parameters for calculating energy losses between steam generator system and porous medium.

Parameter	Value
r_1	0.0046 m
r_2	0.0064 m
L	0.63 m
T_s	30 °C
K	16.3 W·m-1·°C-1*
h_∞	12.74 W·m-2·°C-1

Value taken from [34,35]

The parameters in Table S1 were calculated from correlations that relate the conditions in the surroundings of the system considered with the heat transfer mechanism through the Reynolds and Nusselt dimensional numbers [34].

Finally, based on the quality and desired injection temperature in the porous medium, an energy balance is made (Eq. S6) to know the conditions under which the steam must be generated.

$$\dot{h}_{in} = \dot{h}_{out} + Q_L \quad \text{(S6)}$$

where, $\dot{h}_{in}$ is the energy flow of the steam at the generator outlet (W), and $\dot{h}_{out}$ is the energy flow of the steam at the porous media inlet (W). With the energy flow of the steam at the generator outlet and the mass flow of water, the specific enthalpy is obtained, which together with the temperature and pressure of the system, specifies the necessary conditions to get the desired quality at the porous media inlet.

From the sensitivity analysis of the heat losses with the water, it was obtained that the quality losses between the steam generator and the porous medium inlet do not exceed 3 %. For this reason, steam injection at X = 0.5 was done at 210 ° C and 1.90 MPa (276 psi). Also, the steam generator was regulated so that the energy delivered to the water was sufficient to achieve quality conditions of 0.52, this to ensure injection into the porous medium with a quality of 0.5. For the injection of saturated steam (quality, X = 1.0), the model allowed identifying low heat losses. In this way, a superheated steam condition was sought close to the saturated steam conditions; these conditions were achieved with a temperature of 210 ° C and pressure of 1.44 MPa (210 psi).

For the porous medium, the heat losses due to convection mechanisms inside the medium and by conduction through the walls containing the porous medium are considered.

The convection coefficient in the porous medium is calculated through the following equations [36].

$$Nu = 0.9898(\mathrm{Re})^{0.399} \quad \text{(S7)}$$

$$h_{pm} = \frac{NuK_l}{d_g} \quad \text{(S8)}$$

where, Nu is the Nusselt number of the porous media, Re is the Reynolds number, h_{pm} is the convective coefficient in the porous medium (W·m^{-2}·°C^{-1}), K_l is the fluid thermal conductivity (W·m^{-1}·°C^{-1}), and d_g is the mean diameter of the grains in the porous medium (m), this last value is 0.00003 m.

In the same way as in the injection system, the porous medium is divided into 15 cm sections and the losses in each of these sections are calculated. This is done in order to know the point where the injected fluid completely condenses.

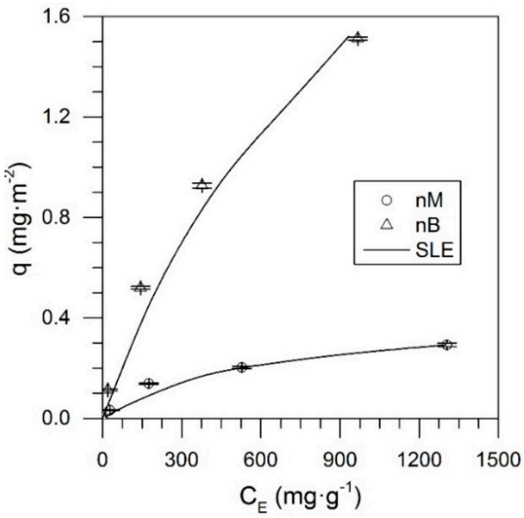

Figure S2. Asphaltene adsorption isotherm over monometallic nanoparticles AlNi1 (nM), and bimetallic nanoparticles AlNi1Pd1 (nB) at 25 °C. The solid lines are the SLE model and the symbols are the experimental data.

Table S2. Estimated parameters of the SLE model for the asphaltene adsorption isotherms over AlNi1, and AlNi1Pd1 nanoparticles.

Nanoparticles	H ($mg \cdot g^{-1}$)	K x 10^{-4} ($g \cdot g^{-1}$)	Nm ($mg \cdot m^{-2}$)	R^2	RMS (%)
AlNi1	2.24	2.00	0.29	0.99	0.61
AlNi1Pd1	1.27	2.01	1.52	0.99	0.24