2D Axisymmetric Temperature Profile Modelling of a Delayed Coking Drum During Pre-Run Warm Up

Pedro Amorim Valenca[1]*, Amaka Waturuocha[1], Keith Wisecarver[1]
[1]University of Tulsa
*800 South Tucker Drive, Tulsa, OK, 74104, pea475@utulsa.edu

Abstract: Delayed Coking is a "bottom of barrel" refining process. A typical feed to this unit is heavy petroleum residue. Before processing the residue, the pilot coke drums receive nitrogen gas, as a way to check restrictions in the flow lines, and to pre-heat the unit at a given temperature among other safety and process reasons. A 2D axisymmetric stationary model was created in order to simulate this pre-run condition with nitrogen gas, as an attempt to calibrate the model before simulating with an oil residue. The single-phase laminar flow and the heat transfer in fluids modules were used simultaneously. The results show that the model predicts a linear trend for the temperature profile as obtained in the experimental run. It also shows that the model matched the boundary conditions for temperature, without presenting any overshoots. Moreover, due to a vanishingly Reynolds number of 0.09, the radial temperature across the coke drum is held constant, varying only in the z direction. In addition to that, the temperatures obtained within the model fits well with experimental temperatures. The heat flux calculated by the model shows a linear trend similar to that observed for the temperature.

Keywords: Delayed Coking, Coke Drum, Temperature Profile.

1. Introduction

Delayed coking is a semi-batch refining process, in which feeds, such as the bottom product from the atmospheric distillation tower and the bottom product from the vacuum distillation tower, are thermally cracked at high temperatures (around 900°F). Hydrocarbon gases, light cuts (such as naphtha) and heavy cuts (such as light and heavy coker gasoil) are products of this cracking reaction, together with the petroleum coke, a solid carbon compound that is not formed in the furnace (while the process feed is being heated), but in the coke drums. Thus the process is called delayed coking. The reactions products then go to a fractionation tower, where they are separated from each other and are then sent for further processing.

Involved in this process, various complex phenomena (such as multiphase flow, thermal cracking reactions, flow through porous media, foaming, among others) take place at the same time, making the modeling and simulation task of this process a daunting challenge. However, if designed properly, the delayed coking model will be of a great help for the refineries. Depending of the complexity of the model, the refineries will be able to observe the temperature profile of the different unit operations involved on delayed coking, obtain reaction yields for different feeds, among innumerous other reasons.

Before the start of delayed coking process, the furnace attached to the coke drum (Figure 1) undergoes a pre-run warm up, in order pre-heat the furnace and the coke drum before receiving the actual oil feed and to check if all the experimental conditions will be obeyed during the actual test. This warm up is done using an inert gas, such as N_2.

Figure 1. Pilot Unit from University of Tulsa Delayed Coking Project, showing the coke drum and the furnace in the bottom.

Therefore, staying in this same scope, it is important to check if a model will also reproduce the characteristics of this pre-run warm up, since its complexity is less than the actual refining process using an oil residue feed. This way, if performed correctly, this pre-run model can be used as a calibration step of the model. This leads to the objective of this paper, which is to create of a 2D axisymmetric model of a coke drum to obtain its temperature and flow profile during the pre-run warm up.

The model will reproduce the coke drum of the University of Tulsa Delayed Coking Project. All the data used in this study was obtained in this facility.

2. MODELLING

The model built for this steady state study did use of the 2-D axisymmetric geometry, laminar flow module and heat transfer in fluids module for the flow and heat transfer simulations. The 3" X 76" SS 316L coke drum was represented by a 1.5" X 76" rectangle.

For the laminar flow module, the Navier-Stokes equations were used. They describe the conservation of mass (Equation 1), conservation of momentum (Equation 2) and conservation of energy in terms of temperature (Equation 3). The fluid parameters (such as density, viscosity, heat capacity at constant pressure, thermal conductivity and heat capacity ratios) were obtained using the N_2 properties built in the software. The fluid is assumed to be Newtonian. The pressure across the coke drum set as 15 psig and the inlet flow rate is set to be 2 ft^3/h, such as the one observed experimentally.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \qquad (Equation\ 1)$$

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u} \cdot \nabla)\mathbf{u} = \nabla \cdot [-\mathrm{p}\mathbf{I} + \tau] + \boldsymbol{F} \qquad (Equation\ 2)$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + (u \cdot \nabla)T\right) = -(\nabla \cdot \boldsymbol{q}) + \tau : \frac{1}{2}(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T) - \frac{T}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p \left(\frac{\partial p}{\partial t} + (\boldsymbol{u} \cdot \nabla)p\right) + \boldsymbol{Q} \qquad (Equation\ 3)$$

For the heat transfer in fluids module, the experimental temperature data obtained from the thermocouples equally spaced throughout the coke drum was used to obtain the values for the boundary conditions and initial condition. These temperature data for each thermocouple were averaged, and at z=0, the temperature was set to be 900°F. A convective heat flux boundary condition was set at the wall, with the heat transfer coefficient of 44.78 W/m^2*K. This was calculated using the Nusselt number for constant wall heat flux and Laminar Newtonian flow (Equation 4) of 4.364 and the thermal conductivity of stainless steel 316 at 900°F obtained in material built-in the software.

$$Nu = \frac{hD}{k} = 4.364 \qquad (Equation\ 4)$$

For the temperature value, a linear equation (Equation 5), with R^2 of 0.9028 (Figure 2), obtained from the experimental data, was used.

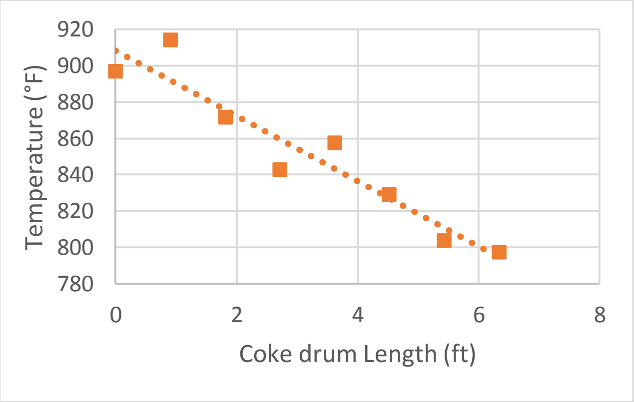

Figure 2. Experimental temperature values obtained during the pre-run warm up.

$$T = -17.928x + 908.29 \qquad (Equation\ 5)$$

Finally, the mesh used in the model was a physics-controlled mesh, with fine element sizes, having the total of 161061 elements.

3. Results and Discussion

The model created is a good representation of what actually happens during the pre-run warm-up. The velocity profile (Figure 3), together with the average Reynolds number (Figure 4) at the center of the coke drum, corroborates for the expected Laminar flow profile.

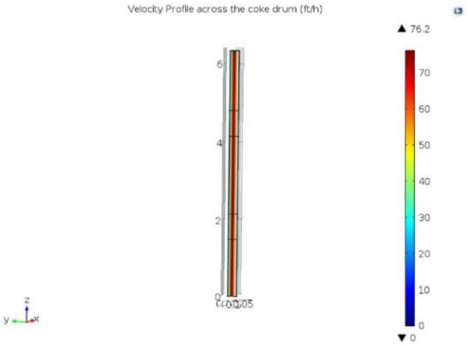

Figure 3. Velocity profile across the coke drum, with maximum velocity of 76.2 ft/h.

The low values obtained for these parameters show the characteristic of creeping flow to the model, which is an acceptable result, based on the very low and slow flow rate of 2 ft³/h of N_2.

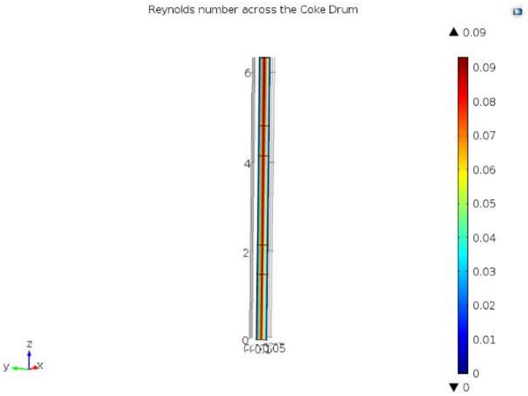

Figure 4. Reynolds number across the coke drum during the pre-run warm up.

The results found for the fluid flow parameters are carried over to the heat transfer analysis of the model, this is reflected especially in the temperature profile obtained for the model (Figure 5), with the radial temperature held constant, varying only in the z-direction. This result can be explained by the low Reynolds number. Since the viscous forces are really small, they do not create any barriers to the heat transfer, which happens instantaneously.

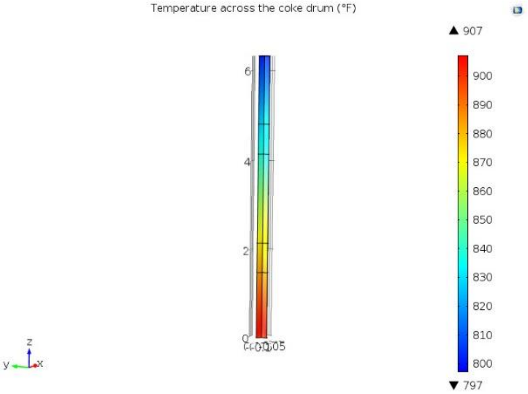

Figure 5. Temperature profile, in °F, across the coke drum, showing the instantaneous heat transfer taking place in the reactor.

Moreover, the temperature values obtained with the model fit well with the experimental values (Figure 6), although the model temperature profile presents a small bump in both ends of the coke drum. These bumps exist because the model tried to achieve the experimental values for temperature and the temperature value set for boundary condition is smaller than the one obtained experimentally.

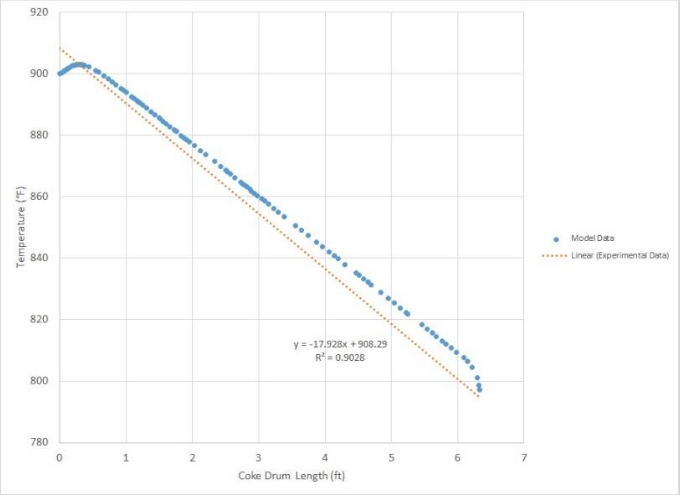

Figure 6. Fit between the model temperature data (in blue) and the experimental temperature data (in orange).

Finally, the heat flux calculated across the coke drum (Figure 7) shows a similar linear profile, like the one obtained for the temperature.

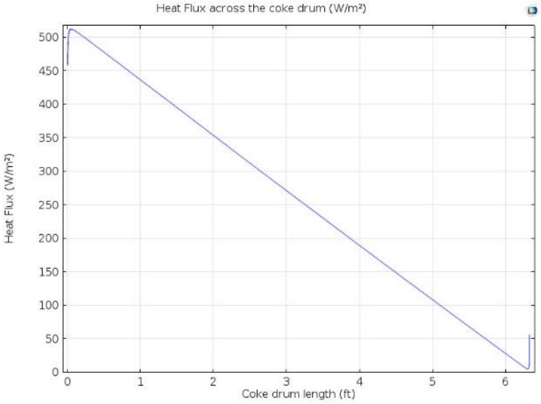

Figure 7. Heat flux across the coke drum, showing the amount of heat needed to keep the experimental conditions constant during the experiment.

4. Conclusion

The model achieved its objective, depicting well the coke drum's behavior during the pre-run warm up. The considerations and assumptions made while setting up the laminar flow module and heat transfer in fluids module allowed the model to show the creeping flow characteristics; a low velocity (76.2 ft/h at the center of the coke drum) and a low Reynolds number of 0.09, both results of the small inlet flow rate of N_2 of 2 ft^3/h.

The low Reynolds number is reflected in the temperature profile results. Due to the flow's really low viscous resistance, the heat transfer in the coke drum occurs instantaneously, making the temperature vary in the vertical axis, while being constant in the radial axis. The temperature values obtained in the model are a good representation of those obtained experimentally, maintaining the linear temperature profile found experimentally.

The model will be tested using the data from experiments with residue. It will also be expanded to represent the reactions occurring inside the coke drum and the multiphase flow generated by those reactions. Phenomena such as flow through porous media, foaming and chimney effect will be a part of this study, that may be expanded for the other portions of the delayed coking process.

5. Nomenclature

ρ: Fluid density (SI unit: kg/m3)
u: Velocity vector (SI unit: m/s)
p: Pressure (SI unit: Pa)
τ: Viscous stress tensor (SI unit: Pa)
F: Volume force vector (SI unit: N/m3)
Cp: Specific heat capacity at constant pressure (SI unit: J/(kg·K))
T: The absolute temperature (SI unit: K)
q: Heat flux vector (SI unit: W/m2)
Q: Heat sources (SI unit: W/m3)
h: Heat Transfer Coefficient (SI unit: W/m^2*K)
Nu: Nusselt number
k: Thermal conductivity (SI unit: W/m*K)

6. Acknowledgements

The authors thank the University of Tulsa Delayed Coking Project Members, staff and Michael Volk for all the support and contribution given to this paper.

7. References

1. COMSOL, *CFD Module User's Guide,* 117-119. COMSOL, Burlington (2014).
2. BIRD, R. Byron, STEWART, Warren E.; LIGHTFOOT, Edwin N, *Transport Phenomena*, 430. John Wiley & Sons, New York (2007).
3. PRYOR, Roger, *Multiphysics modeling using COMSOL: A First Principles Approach*, 225-319. Jones and Bartlett Publishers, Boston (2011).
4. COMSOL, *Introduction to CFD Module*, 5-14. COMSOL, Burlington (2014).