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Study of pressure and temperature developing profiles in crude oil pipe flows

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ABSTRACT

Pressure and temperature developing profiles for crude oil transportation pipelines are simulated under a diversity of external boundary conditions. MOLCV is used in this research to convert a system of partial differential equations into a system of ordinary first order differential equations in cylindrical coordinates. Momentum and energy balance equations are coupled in crude oil flows because of thermal–physical property variations. Simulation solutions show the effect of boundary conditions in the pressure drop profile, which provide potential model predictive applications to account for weather forecast in crude oil transportation operations.

1. Introduction

The study of laminar forced convection in cylindrical ducts with variable thermal fluid properties is of great interest in the design of crude oil transportation pipelines. The high viscosity and heat losses to ambient temperatures make crude oil distribution challenging, especially when viscous fluids are transported long distances from production to consumption sites (Pierce, 2007). Moreover, heavy oil seems to be a prominent energy alternative in the presence of high demand of declining conventional petroleum reserves (Clark, 2007). Fig. 1 illustrates a recent expansion project to transport heavy crude oil from Canada to the USA. This expansion would increase the amount of crude imported to USA by approximately 450,000 barrels per day. This heavy crude option is limited, not by the amount available in the reserves, but by difficulties in its transportation due to high viscosities at ambient temperatures (Olsena and Ramzela, 1992).

Transportation of heavy oil to distant refineries adds significantly to the cost of heavy oil production and consumption. New technologies for heavy oil transportation are therefore being developed to make this energy source affordable to consumers (Ahmed et al., 1999) (Bannwart, 2001) (da Silva et al., 2006). Among the different techniques available for reducing flow resistance is the use of drag-reduction additives either through the addition of light oil or by the creation of oil–water emulsions (Al-Roomia et al., 2004). However, these solutions remain costly either due to the cost of expensive chemical additives, the reduction of the mixture energy content, or because of the need for an extra separation step to make the mixture ready for consumption. A second approach considered in this work is to reduce flow resistance in crude transportation by warming up the fluid, which is limited by safety regulations. The consumption of significant amounts of energy to warm crude oil and reduce the transported fluid viscosity indicates the need for rigorous simulations that can determine the pressure drop and velocity profiles inside cylindrical pipes. This research simulates this type of fluid transportation problem with the same external boundary conditions to which pipelines are exposed in practice.

Simulation problems solved in the current literature usually consider uniform temperature conditions or constant heat flux at the surface, even though crude oil pipelines are exposed to variable convection conditions. External forced and natural convection can be incorporated in numerical methods as boundary conditions by estimating a surface temperature. This estimation is based on the external fluid conditions and internal fluid temperature at the vicinity of the pipe inner wall. Dunia and Guzman(1987) considered light and medium crude oil flows in cylindrical pipes with variable viscosity and external natural convective condition. The analysis of variable viscosity flows in laminar regime requires the simultaneous solution of mass conservation, momentum and energy equations, all while incorporating empirical correlations for the variation of thermal-fluid properties. The difficulty in considering all these equations simultaneously forces any solution to be numerical in nature. Fortunately, the use of numerical techniques to solve complex thermal fluid problems

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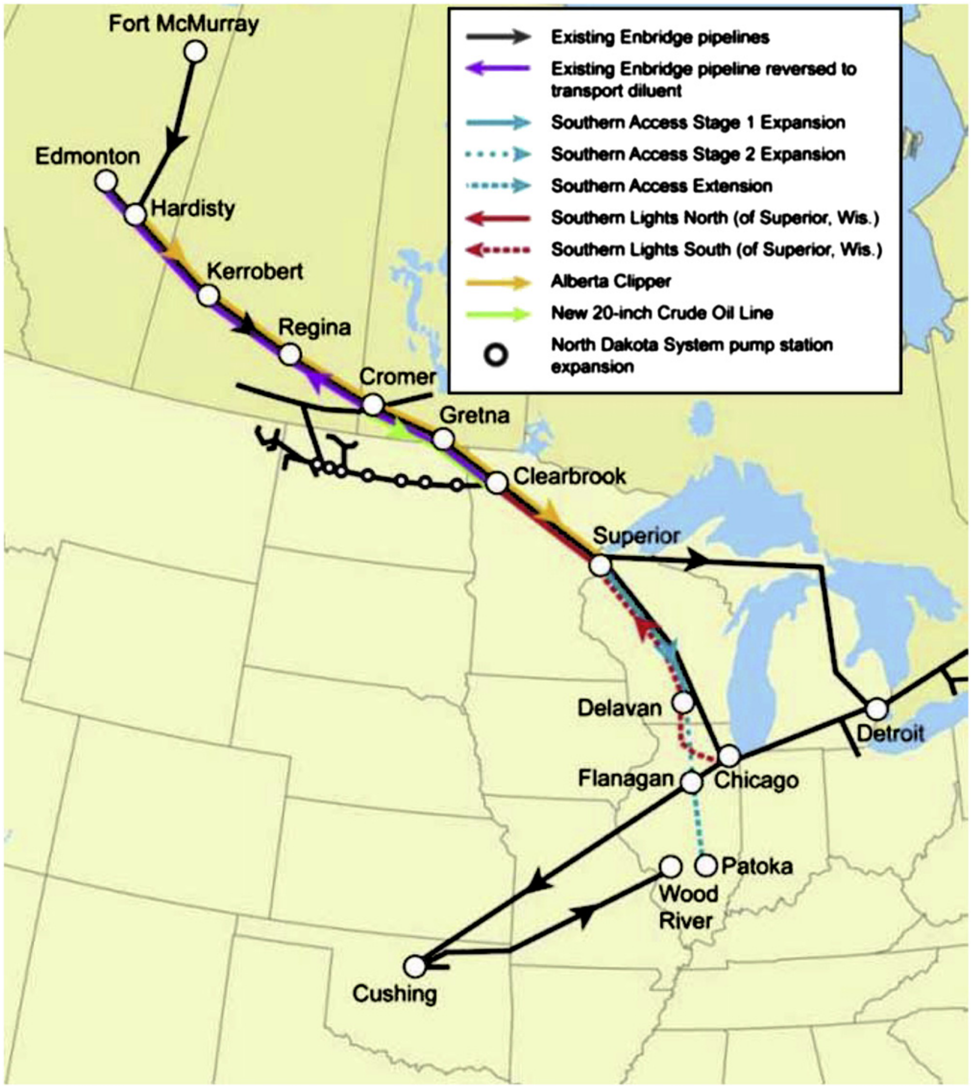

Fig. 1. Enbridge proposal pipeline expansion, increasing the delivery of crude oil from Canada to the USA by more than 450,000 barrels per day (Electronic-News-Builder, na).

increases the number of applications and flow conditions that can be studied. The Method of Lines (MOL) and Method of Lines with Control Volumes (MOLCV) are numerical methods developed by Liskovets (na). MOL converts a system of partial differential equations into a system of ordinary first order differential equations.

The purpose of this research is to extend the application cases presented in Dunia and Guzman(1987) by expanding the use of MOLCV in a way that could be implemented in situations where variable boundary condition information is gathered in real time. The MOLCV solution methodology used in Dunia and Guzman, 1987) has been validated with the results given by Faghri(na), Hornbeck(1964), Hwang and Sheu(1974) and Manohar(1969). Even though the MOLCV algorithm used in this work has been validated in previous publications, there is no existent literature data to compare the simulation results obtained in this research. Nevertheless, the solutions demonstrated in this work provide important insight to develop a pilot plant prototype that accounts for heavy crude oil flows, up to date thermal–physical correlations and variable boundary conditions. The current need for crude oil transportation prototypes is also driven by fast and more affordable data acquisition equipment that can be used for optimal operations. This work demonstrates that MOLCV can be used for time dependent boundary conditions given by sensors that detect weather changing conditions.

This paper is divided in the following manner: Section 2 presents first-principle model equations and boundary conditions considered in this work. It also introduces the different viscosity correlations that will be used for crude oil flows. Section 3 shows how the equations and boundary conditions presented in Section 2 are made dimensionless and are discretized. The solution procedure using MOLCV is presented in Section 4. Three simulation cases related to crude oil flow but using different boundary conditions and viscosity correlations are demonstrated as examples in Section 5. Conclusions and potential applications for future implementation are provided in Section 6.

2. Problem formulation

This work exploits the use of dimensionless quantities for the problem definition and solution description. Empirical correlations are used here to describe the effect of the temperature in the fluid viscosity as well as the effect of ambient conditions in the calculation of the external convection at the pipe surface. The entrance temperature profile is always considered uniform. However, velocity profiles are considered either uniform or fully developed when entering a warming up or cooling downpipe section.