

## Determination of pressure needed to restart a pipeline containing non-Newtonian oil at or below the pour point

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Winter on the North Slope of Alaska presents challenges to the operators of petroleum production facilities. In particular, oil export lines can become blocked with either gel or high viscosity oil when the line is shut-down and the oil is allowed to cool. The blockage occurs when there is insufficient pressure to move either gel or oil near its pour point. To avoid this condition, a shut-down/restart procedure needs to be developed to provide the operators guidance regarding the options available to them. The procedure must cover both planned and emergency shut-downs. A key element in developing the procedure is knowledge of the restart pressure requirement as a function of the time that the oil has been allowed to cool. Of course, the initial temperature profile of the line prior to shut-down and the ambient temperature are additional variables that must be included in both the analysis and the resulting procedure.

The viscosity of oil containing even a small amount of waxy compounds (e.g. normal paraffins) increases dramatically as the temperature is lowered below the wax appearance temperature. The fluid behaviour becomes non-Newtonian as the amount of wax solids increases. When the oil temperature reaches the pour point, the oil becomes a gel with even different behaviour from a rheological point of view. Usually, the gel requires a yield stress to be exceeded before flow will initiate.

There have been several investigations (e.g. [1]) of the restart of lines that have gel throughout the cross section of the pipe and for a large length of the pipe. The models developed in the prior studies require special rheological tests (e.g. controlled stress Rheometer and model pipeline tests) to determine the gel's yield requirement. Often the shear history of the oil prior to gelation is also important. Those analytical approaches are certainly appropriate for the case of complete gelation. In our studies of a particular pipeline on the North Slope, we found that the available pump discharge pressure at the pipeline inlet would be exceeded well before the line had become fully gelled. The increased viscosity alone was sufficient to require the line be emptied after a given shut-in time.

In other cases, there may be sufficient pressure to allow some gel to form on the pipe wall. To examine those cases, a two dimensional dynamic shut-down model was developed that determined the axial and radial temperature profiles of the oil as a function of

cooling time. The gelled regions were defined by oil temperatures below the pour point. In addition, a restart model was developed that determined the temperature and pressure history during the restart operation. In one form of the restart model, the gel layer was not allowed to change once formed. In another form of the restart model, the gel layer thickness was dynamic as determined by a heat balance on the gel layer. In this latter restart model, the gel layer disappeared as the oil temperature exceeded the pour point. The differences in the pressure requirements between these two restart models were not great. The greatest difference occurred for cases where gel had just begun to form.

In some emergency shut-down scenarios, the pipeline may have been de-inventoried by pigging. Then the question arises: can the cold line be refilled without the use of a leading slug of non-gelling oil (e.g. diesel)? To answer that question, a refill model was developed. This model allows a gel layer to form in the oil at the liquid front, but that layer then disappears as the local temperature increases due to the warmer oil behind the front. The simulation shows a gel layer "travelling" down the pipeline with time. The thickness of this layer grows as the liquid front cools while it travels down the line. In the pipeline examined, it was found that diesel was not needed for the refill operation.

The one dimensional, dynamic restart and refill models allow for either laminar or turbulent flow. They also allow for the fluid to be either Newtonian or non-Newtonian depending upon the local temperature. The flow was assumed to be incompressible thereby allowing the flow rate to be specified as a function of time. This allowed the pipeline and wall dynamic heat balances to be solved first with a known velocity, and then the momentum balance was solved to obtain the inlet pressure requirement.

The rheological measurements required for the restart and refill models include viscosity at several shear rates in the temperature range of interest and measurement of the pour point. Yield stress and shear history for the gel are not required to develop a decision tree for the shut-down and restart operating procedure.

### References

- [1] Lee, H.S., Singh, P., Thomason, W.H., Fogler, H.S. (2008) Energy and Fuels 22, 480-487.