To: Pat Dougan
From: Dan Joseph

Research Proposal to Syncrude Canada

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INTRODUCTION AND SUMMARY OF PREVIOUS CONTRIBUTIONS

This research proposal was submitted to Ken Sury on February 17 and was funded at a reduced level for one half the year period, June 1997 - June 1998 originally proposed. I am seeking a budget for the second period. I am asking for this second half year funding to be given to the University of Minnesota for the period Jan. 1 to June 1. I would also like to have my personal consulting contract renewed for the same period; this contract is included in this packet for your convenience. I don't think that the description of my duties needs to be changed.

Sections I and II below are exactly what was proposed to Ken on Feb. 17, 1997. Since these topics were proposed for one year, they are still under investigation. Now I added a section III called "Results and future work" to make explicit what we hope to achieve in the next period.

Here, before sections I, II, and III, I would like to summarize some of our contributions to the Aurora project so far.

- Established that long term self-lubricated pipelining was possible without pressure build-up.
- Found the procedures to start-up self-lubricated pipelining and wrote Syncrude's pre-patent application for these procedures.
- Identified the mechanisms of self-lubrication associated with clay covering of bitumen which prevent bitumen from sticking to itself, promoting the coalescence of clay water into lubricating sheets. I also prepared the pre-patent for this technology.
- The two patents are:
  - NS305. Technique to promote lubrication of bitumen through the addition of colloidal particles in the water by D.D. Joseph, K.N. Sury and C. Grant.
  - NS306. Method for establishing self-lubricated flow of bitumen froth or heavy oil in a pipeline by D.D. Joseph, R. Bai, O. Neiman, K. Sury and C. Grant.
- We verified that restart was easy after short shut downs and showed theoretically that a stopped line could always be restarted and experimentally that the pipeline could be cleaned by running clay water, without pigging. <u>There are no show stoppers</u>.

- We collected pressure gradient vs. flow speed data and recently added pressure gradient vs. temperature, highlighting the important role of frictional heating.
- Our results motivated the construction of the 24" pilot loop in Fort McMurray. We reduced this data, Neiman's two-inch pipeline data and our 1" data and found the scale-up law; the pressure gradient is proportional to $U^{7/4}/R_o^{3/4}$ where U is the flow velocity and R_o the pipe radius and the constant of proportionality is 10 or 20 times greater than water, depending on the temperature.
- We have shown in our one-inch pipe that a lubrication result more favorable than the one above occurs spontaneously at high velocities (larger than 1.6 m/sec in our 1" line). This better lubrication appears to be associated with the temperature rise associated with frictional heating.

In section III I am going to propose more studies which should add value to the Aurora pipeline project.

I am sure that Syncrude recognizes the significant investment we made to modify our pipeline loop to meet Syncrude's test objectives. In view of this and ongoing contributions beyond the scope of the work agreement, I am requesting additional funding.

I. Overview of projects related to self-lubrication of bitumen froth.

1. Factors governing water release

We know that there is a critical velocity for water release leading to lubricated flows. We have conjectured that the release is related to critical shear stress. The underlying fundamentals for water release leading to self-lubrication need further study.

It is necessary to vary froth speed, composition, temperature and pipe diameter at the border between lubricated and non-lubricated flows. These factors, which should enter to understanding of the fundamentals are just the parameters which enter into control of start and restart and are basic to the operation of froth pipelines.

2. Test Facilities

The studies will be carried out in our 1-inch pipeline. We need information on scale up. We want to consider setting up a 2-inch and 1/2-inch pipeline for scale up studies. Perhaps a small facility could be set up in Canada.

We intend to equip our pipeline with an observation sector at the pipe inlet where lubrication is formed and the conditions of lubrication are most severe. It would be useful to examine viewing sections at different locations.

Many useful studies of froth can be carried out between rotating cylinders and parallel rotating plates. These batch studies do not require large amounts of froth, are easy to control and give rise to precise measurement of flow properties.

3. Determination of the effective thickness of the lubricating layer

The effective thickness is related to the amount of free water released. We need to know how the amount of free water varies with froth speed, composition, temperature and pipe diameter. We propose to create a database for free water from experimental measurements on our 1-inch pipe. The free water studies are important for understanding of shear induced release and for the determination of optimal conditions for lubricated transport.

4. Study of wave structure on the froth core

The waves (Tiger waves) on the froth depend on the flow speed and the amount of free water. The wavelength is shorter when the wave speed is larger and when more free water is liberated. Maybe we can find a way to predict the amount of free water from observations of the speed an amplitude of waves.

5. Study the effects of water addition on self-lubrication

I think we should try to know more about how injection of top water effects self-lubrication. This kind of knowledge is needed for restart under difficult conditions.

6. Remedies for fouling

We would look at wall treatments and materials of pipe construction which resist fouling, as we did in the past with cement-lined pipes. We have not tried clay pipes, though we know that clay is highly oleophobic. Clay pipes and clay water might have good synergy; small sections of a pipeline at greatest risk for fouling could be made of clay or clay linings.

The problem of fouling is more severe with heavy crudes than bitumen froth. We could think of collaborations with Intevep in this area. It would be of interest to see if clay water would reduce fouling of Venezuelan crudes.

II. First-year research projects (4/1/97-98)

The three projects listed below are submitted to Syncrude for consideration for the first year's work.

1. Modification and improvement of the test system for the 1" pipeline (3 months)

a). Maintenance of Moyno pump: change the stator (maybe rotor) and the sealing package.

b). Modify test system for loading and unloading froth, clean the pipeline and cover the top of the supply tank. These changes must be done for environmental health and safety, but they can also reduce the waste of froth.

c). Add a cooling system to control the temperature of the test system. We need an additional tank for storing ice or cold water. If the temperature in the system is too high, we turn off the heat and pump cold water through the system.

d). Equip the pipeline with glass or plastic glass sections at the pipe inlet where lubrication is formed and the conditions are most severe. We will examine viewing sections at different locations for each fixed flow speed.

2. Experiments to correlate the pressure gradient, flow rate, free water and wave structure of lubricated flows in the one-inch line (9 months)

We want to create an extensive database for flows with different pressure gradients and flow speeds by systematic variations of the temperature and froth composition.

We need to know how the free water correlates with flow speed to get a handle on the mechanism of water release under shear. We believe that the wave structure is important here and we want to create data in which the flow speed, free water and wave length and structure are measured for each value of the pressure. The wave parameters can be measured with our high-speed video system. It would be desirable to create this date for high and low temperatures, at least, and for relatively dry and we froths.

3. Study the critical shear rate for water release between rotating cylinders and rotating parallel plates.

We would like to build something inexpensive to do this kind of batch testing. The idea is to determine if and what kind of useful data can be obtained from modest equipment. We may evolve a froth tester from this work and it should serve us well in our study of the mechanism of water release.

As usual, the plan proposed may and probably will be changed as dead ends and good opportunities come into evidence.

III. Results and future work

- All the proposed modifications to our 1" pipeline except the viewing section at the inlet were done. It is now easy to download froth and we have the means to control and accurately measure temperatures. Using this improved pipeline we generated the data shown in the figures.
- We are going to repeat these experiments again; this time we will add a hold-up measurement to each data point; that is, stepping up the velocity we collect the pressure gradient, the temperature and the free water at each step. We cannot understand the basic mechanisms for self-lubrication without knowing the free water, or hold-up.
- We have generated the curve of critical velocities for loss of lubrication as a function of temperature (figure III.1). We don't yet now if this value is identical with the minimum critical value for starting self-lubrication.

- We did not look at cement-lined pipes for self-lubrication. I understand that corrosion is an issue and cement linings are a cheap remedy. But I think that synergies between cement and clay water could give rise to desirable hydrodynamic effects of self-lubrication.
- We collaborated with Sean Sanders in the construction of the new 4" test loop in Edmonton. Of course, we hope to be able to think about how the data from this loop impacts our understandings of self-lubrication and to consider the implications of their data for the Aurora project.
- It is necessary to carry out theoretical studies of frictional heating to correlate the temperature data being taken in experiments (see figures III.2 - III.5). This frictional heating could be a major factor controlling froth temperature in the Aurora line.
- We are developing the theory of self-lubrication which was initiated in the paper "Self-lubrication of bitumen froth" by Joseph, Bai, Mata, Sury and Grant. We developed an idea to explain the observed increase of 10 or 20 times the friction of water. It is based on analysis of hold in turbulent flow of water. Now we have done a κ-ε calculation of turbulent flow; if you use the observed pressure gradient you find that the thickness of the turbulent water layer is consistent with our measurements of free water. The κ-ε code could enter as a theoretical tool to support the pipeline project.
- We have constructed a rotating cylinder apparatus, with froth in the annular space between the cylinders, to measure the torque vs. angular velocity when the inner cylinder rotates (see figure III.6). We control the ambient temperature by immersing the apparatus in a water bath. The instrument can be regarded as a froth rheometer. In the experiments reported in figures III.6, the temperature of water bath was fixed at 20^{o}C, 24^{o}C, 26^{o}C 28^{o}C and 30^{o}C.

The froth temperature increases with angular velocity even when the water bath temperature is fixed. The torque begins to oscillate when the temperature rises to about 36^{o}C. This markes a transition to lubrication which is probably associated with a stick-slip regime. At higher RPM the froth enters into a fully lubricated regime characterized by a precepitous drop of torque to values close to those for water alone. The temperature then slowly decreases to values only modestly larger than the temperature (26^{o}) of the water bath.

The froth rheometer may also be used to find values of the torque, angular velocity and temperature for the loss of lubrication. The data for these studies are the torque curves for decreasing RPM. Temperature data for decreasing RPM is not shown. Self-lubrication is abruptly lost at a critical RPM not more than the critical value for the start up of self-lubrication.

So far the results are splendid. We get an increase of torque with angular velocity until a critical value for the sample of froth is reached. Then the torque drops abruptly to almost zero signaling the start of lubrication. When we lower the torque, the lubrication effect is lost. These events are in excellent correspondence with observations in pipelines though the critical values are different.

We have to do more testing. The froth rheometer could be the standard instrument (like a Fann) at pipeline stations. We are preparing a video and a report. Syncrude should consider whether they want to patent this rheometer.

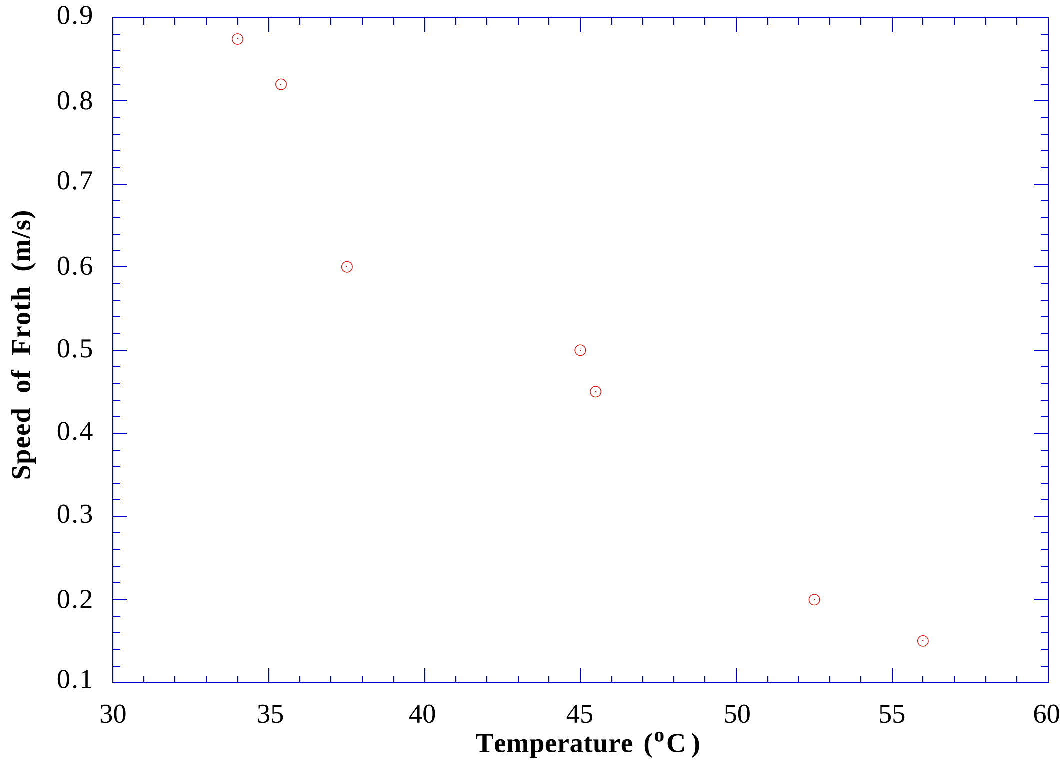

Figure III.1. Froth velocity at which self lubrication is lost as a function of the froth temperature. Self lubrication is more persistent at high temperatures.

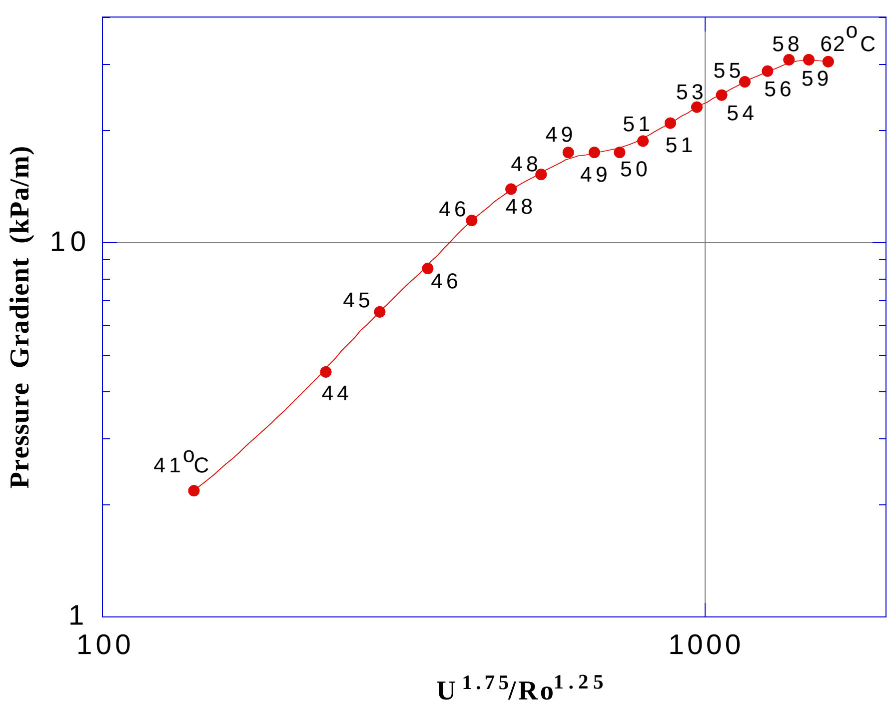

Figure III.2. The pressure gradient vs. Blasius parameter in I" (25mm) diameter pipe. The temperature of the room was 26°C and the froth temperature was nor controlled; the increase in temperature is due to friction heating as shown in Figure III.3.

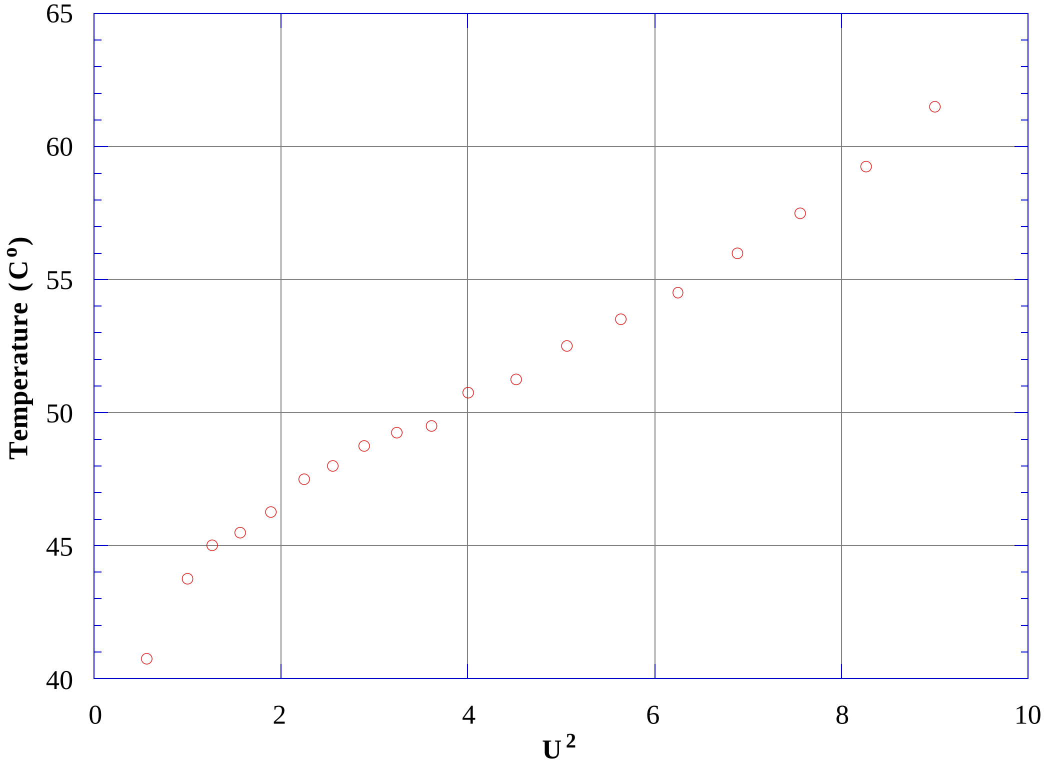

Figure III.3. Temperature vs. the square of the flow speed for conditions specified in Figure III.2. the rise in temperature is approximately linear suggesting friction heating.

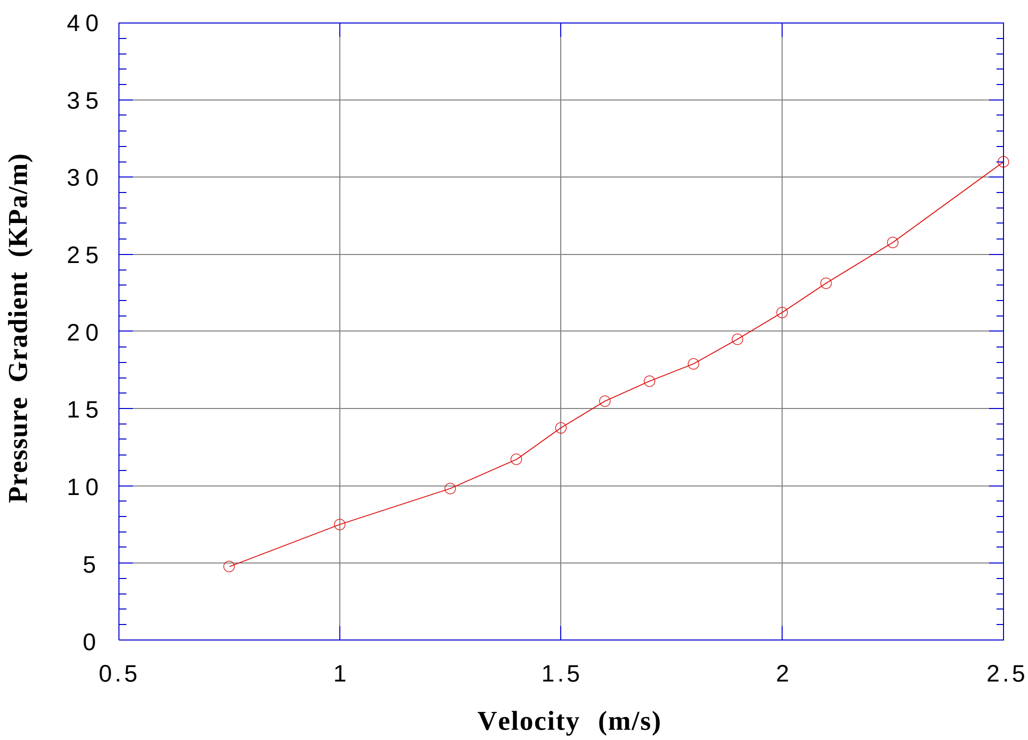

Figure III.4. When froth temperature is fixed at 51°C, the pressure gradient increases slightly faster than linear with flow speed.

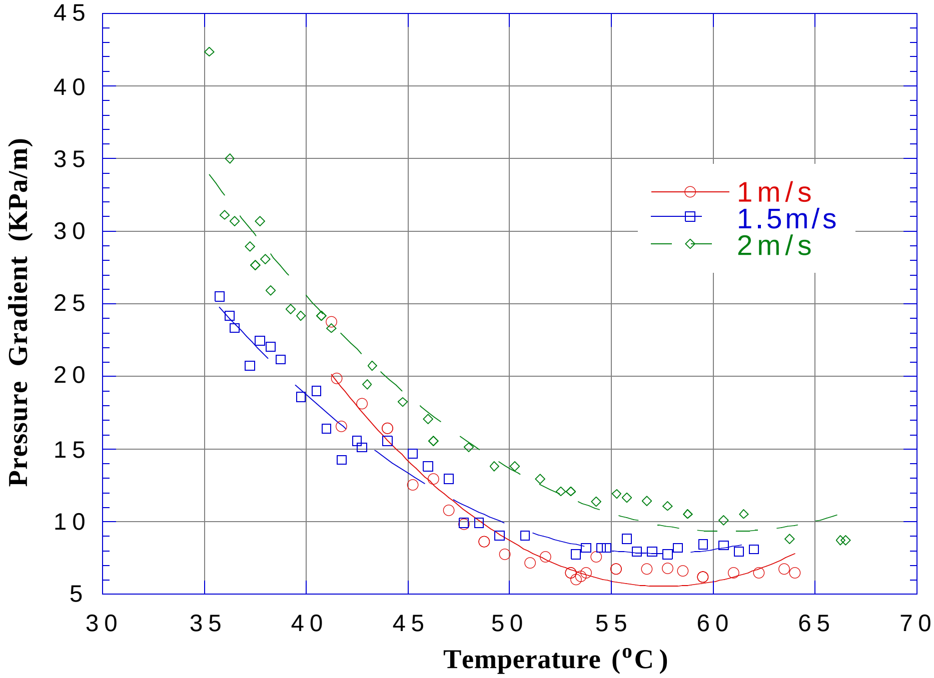

Figure III.5. The pressure gradients decrease with the froth temperature at a fixed flow speed; the temperatures are higher for faster speeds.

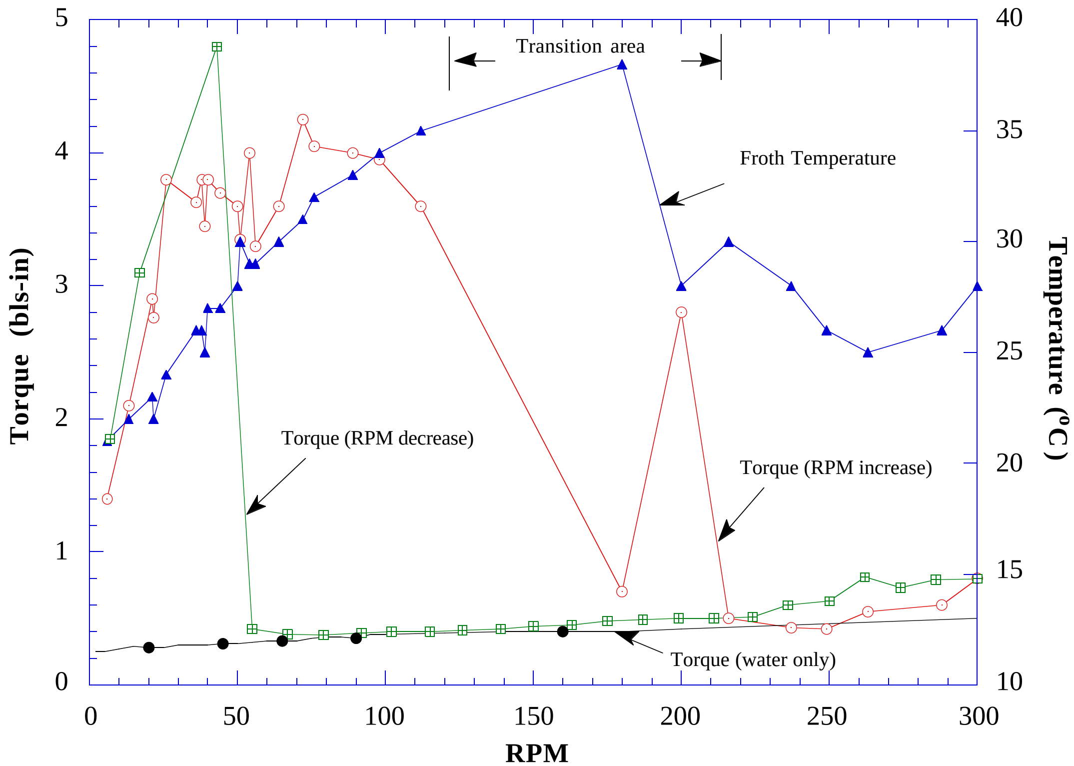

Figure III.6a. Temperature of water bath is fixed at 20^{O}C.

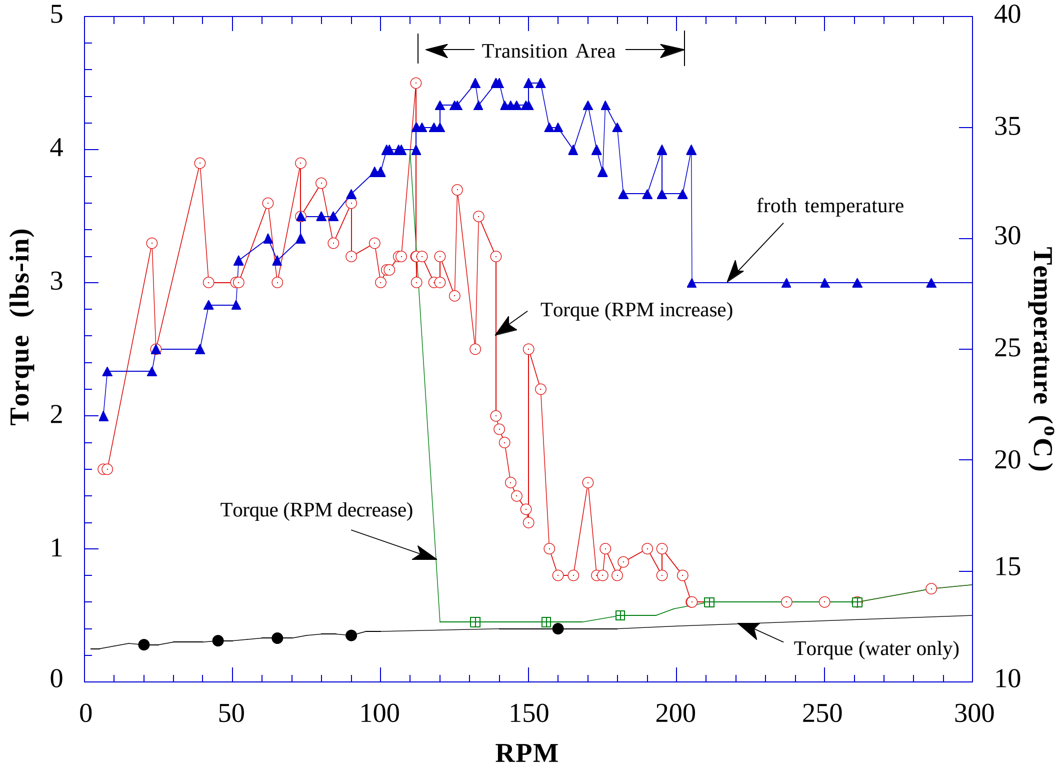

Figure III.6b. Temperature of water bath is fixed at 24°C.

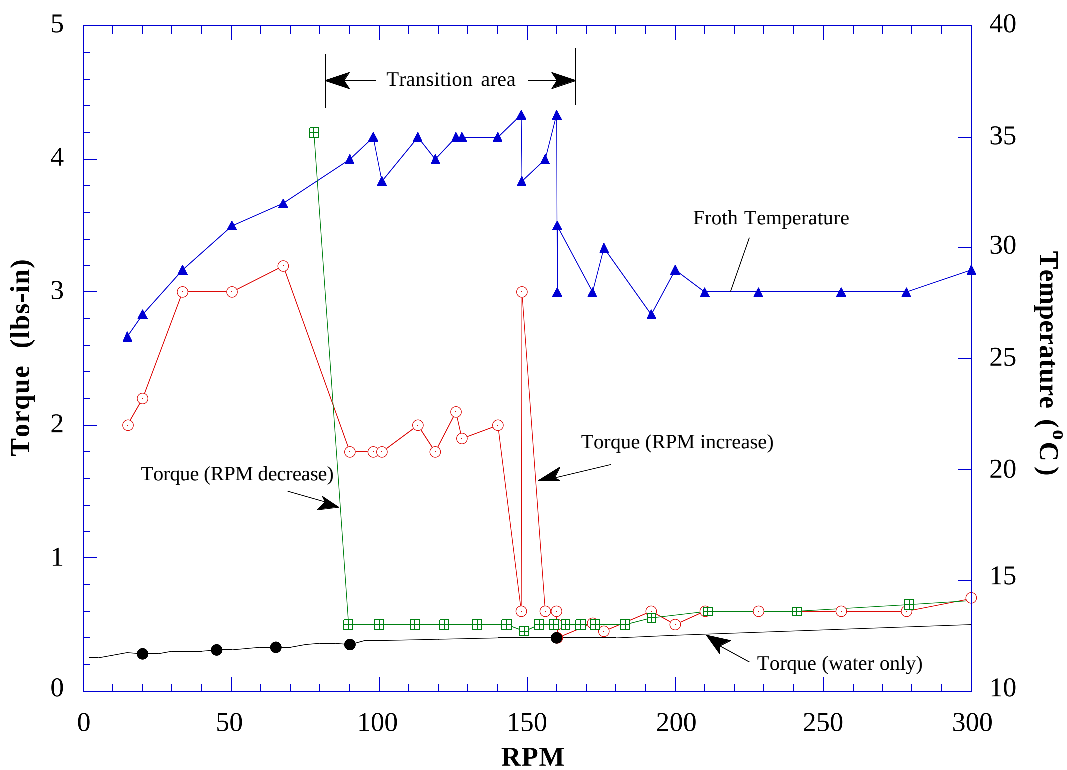

Figure III.6c. Temperature of water bath is fixed at 26°C.

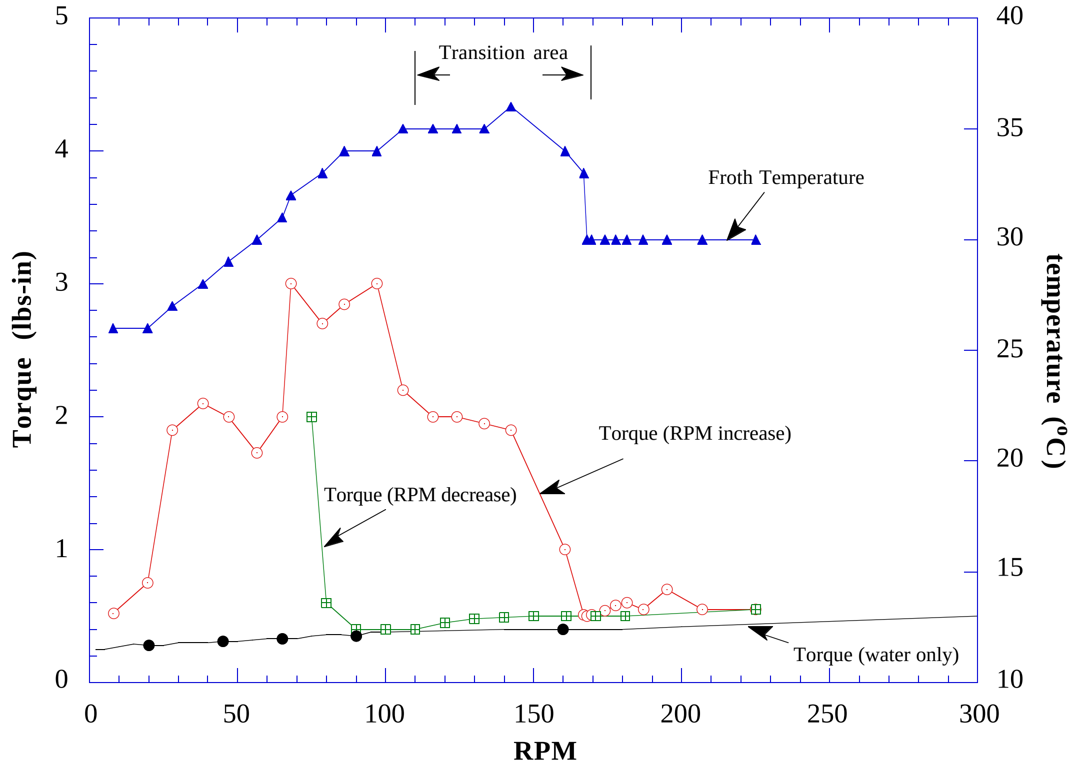

Figure III.6d. Temperature of water bath is fixed at 28^{o}C.

Figure III.6. Rotating cylinder froth rheometer. ○ -- Torque on froth for increasing RPM. ● -- Torque on water for increasing RPM. ■ -- Torque on froth for decreasing RPM. ▲ -- Temperature of froth for increasing RPM. The values of the velocity at the critical RPM for self-lubrication vary between 0.6 and 1 m/s which are in the range of critical velocities for the start of self-lubrication in pipelines. Self-lubrication is lost when the angular velocity is dropped below the transition regime of partial lubrication, or stick-slip.

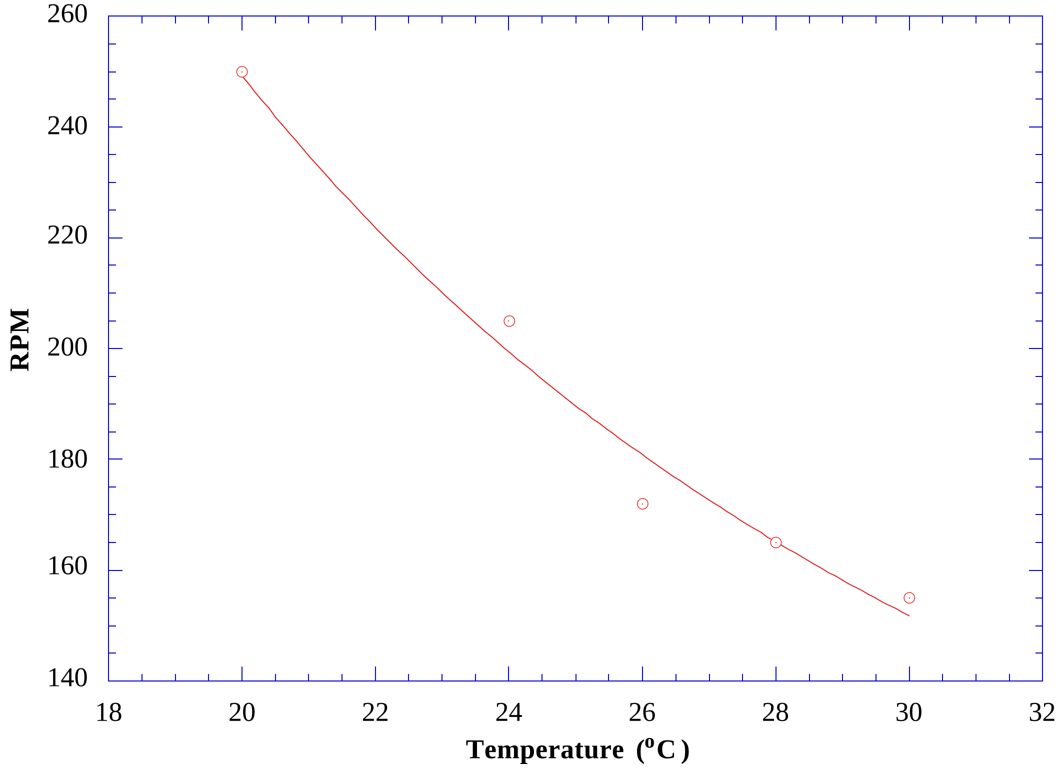

Figure III.7. Critical RPM for transition to full lubrication vs. the temperature of the water bath.