Fermi National Accelerator Laboratory

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CHARACTERIZATION OF TWO PHASE FLOW IN A FERMILAB TEVATRON SATELLITE REFRIGERATOR

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ABSTRACT

A description of the two–phase flow in a Fermilab satellite refrigerator is given. The Tevatron's 24 plants each deliver subcooled helium to two arrays of cryogenic components located in the synchrotron tunnel below ground. At the ends of these arrays, the flow is throttled into the two–phase region and returned in counterflow to the refrigerator. The majority of the liquid in this return flow boils away before leaving the tunnel, thereby maintaining a uniform operating temperature. However, stability considerations require a certain fraction of liquid be returned to the refrigerator.

Since the beginning of Tevatron operation, the nature of this two phase return flow has not been quantified beyond crude estimates using flow rates and assumed heat loads. Recent implementation of a meter for the void fraction of two phase helium flow, combined with a dewar for phase separation of this return stream, has made possible a description of this flow. A discussion of the void fraction meter, together with a dynamic picture of the flow, is presented.

INTRODUCTION

The satellite refrigeration system at Fermilab supplies "single–phase" liquid helium to the superconducting magnets of the Tevatron synchrotron. Magnet design is such that each refrigerator delivers subcooled helium to two "strings" of magnets. At the end of each string, the helium is expanded through a throttle valve into the two–phase region (96% liquid by mass) and returned back to the refrigerator through the magnet strings in counterflow with the subcooled single–phase helium (Fig. 1). Heat is removed from the 120m magnet strings by utilizing the latent heat of the returning two–phase stream; thus a more or less constant temperature profile is maintained. Given the heat load of the strings and the operating pressure of the two–phase stream, one can find the minimum required flow rate necessary to remove the heat. This solution predicts complete consumption of the two–phase flow, resulting in the return of saturated or slightly superheated vapor to the refrigerator. In practice, however, the Tevatron satellites have never been able to operate in this manner. Most likely because of the geometry of the magnet flow passages and the resulting flow velocities, stable refrigerator operation requires additional helium flow through the magnet strings. In powered magnets, a liquid fraction returning to the refrigerator below an estimated 20% results in oscillations in magnet temperatures.

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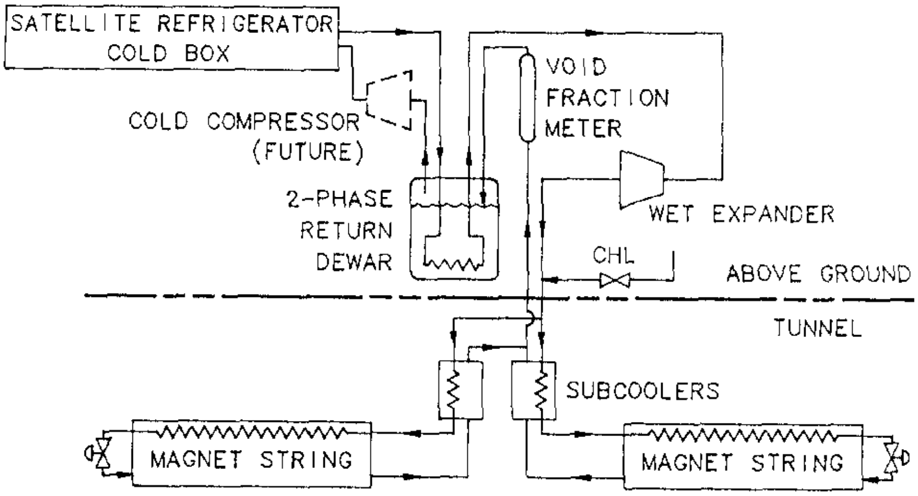

Fig. 1. Fermilab Tevatron satellite refrigerator supplying two magnet strings.

Data collected previously (Fig. 2), during adjustment of the helium flow rates through the magnet strings, indicated that as the flow rate is reduced a level is reached where oscillations in magnet temperature appear. These data represent the degree of superheating of the flow and were taken by measuring the pressure difference between the two–phase circuit and a helium vapor pressure thermometer (VPT) imbedded in the flow near the last magnet in the flow path. As determined from refrigerator flow rate and estimated magnet string heat load, this flow corresponds roughly to the stable operating limit of 20% liquid fraction exiting the strings. The periodic nature of the oscillations suggests some sort of gross separation of the flow. It is postulated that at some particular flow rate, the liquid fraction is no longer carried along with the vapor but rather pools in the bottom of the flow passage, gradually accumulated at the end of the two–phase circuit. When some critical volume of liquid is collected, it is pushed en masse through the remainder of the flow path to the refrigerator by the vapor. Given that the last leg of the two–phase circuit is a nine meter vertical run, the result is a percolation of liquid back to the refrigerator, that is, slugs of pure liquid followed by extended voids of superheated vapor.

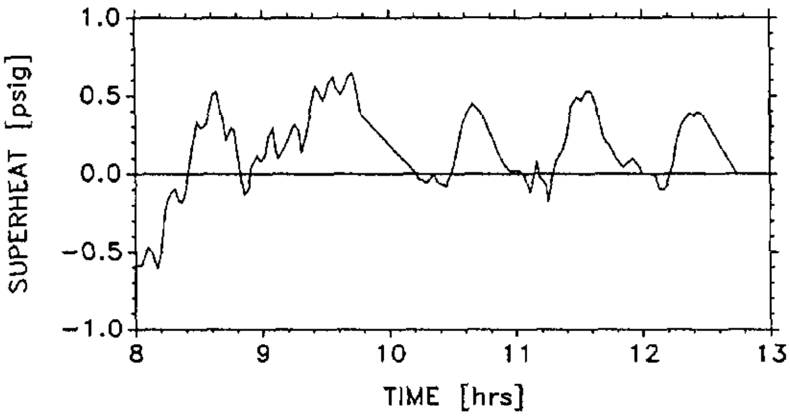

Fig. 2. Oscillations observed in two–phase to VPT pressure difference indicating unstable refrigerator operation.

In order to test this theory, efforts were undertaken to directly measure the void fraction of the helium in the two–phase circuit as it exits the vertical leg on its way to the refrigerator. The remainder of the paper describes the development of the required meter, tests on the unit, and results when installed in a Tevatron satellite.

MEASUREMENT TECHNIQUE

The volume fractions of liquid and vapor in a two phase flow between plates of a capacitor has been measured in research settings on quite a few occasions [1,2,3,4]. The principle of this measurement lies in changes in the capacitor value due to difference in dielectric constant between liquid and vapor phases of the fluid, which in the case of helium at 4K is about 4%. Measurements of the capacitance value can be related directly to the flow quality (fraction of vapor by mass) if it can be determined that the flow is homogeneous, that is, the vapor and liquid are both moving at the same velocity and are evenly distributed across the flow cross section. Otherwise two–phase flow correlations can be used with volume fraction measurements to arrive at flow quality. The particular configuration of the capacitor sensor influence the accuracy of a void fraction meter, which generally must be sized for a specific application. For instance, with parallel flat plates, differing two–phase flow patterns do not appreciably alter void fraction readings since the electric field is nearly constant[3]. Between concentric cylinders, the capacitance is a function of where in the flow annulus the two fluid phases reside[4]. In the cylindrical configuration, void fraction measurement uncertainty due to the capacitor sensor can be improved by using a small gap and large diameter.

Measurement of changes in the capacitor value is accomplished most accurately by using the well established frequency measurement technique. Here, the capacitor sensor serves as a component of an oscillator circuit having a highly discernable output frequency, albeit an output of narrow band at high frequency. The particular circuit board used in this investigation is a Clapp type oscillator capable of operating in liquid helium. It was supplied by P. Dullenkopf and is fully described elsewhere[3]. The equation:

$$f_{osc} = \frac{1}{2\pi(LC_{osc})^{1/2}} \tag{1}$$

governs the measured oscillator frequency, f_{osc}, where L is the known oscillator circuit inductance, and C_{osc} is the effective oscillator capacitance. C_{osc} is a function of the capacitor sensor, C_m, as well as unknown "parasitic" capacitance, C_p, and known circuit capacitance, C_s.

$$C_{osc} = \frac{C_s(C_m + C_p)}{C_s + C_m + C_p} = \frac{C_s(C_o\varepsilon_{tp} + C_p)}{C_s + C_o\varepsilon_{tp} + C_p} \tag{2}$$

For the case of a concentric cylinder sensor with inner tube diameter a, outer tube diameter b, and length ℓ, C_m would ideally be given by $C_{m,\,ideal} = 2\pi\ell\varepsilon_o\varepsilon_{tp}/\ln(b/a)$. However, as a practical notation in Eq. (2) the geometry and dielectric of free space, ε_o, are lumped into a constant capacitor "characteristic", C_o, and the definition $C_m = C_o\,\varepsilon_{tp}$ is used. Determination of C_o and C_p result from calibrations described below. ε_{tp} is the effective dielectric constant of the two–phase flow. Also, by definition, void fraction, y, of a homogeneous flow is related to the essentially measured value of ε_{tp} by:

$$y = \frac{\varepsilon_f - \varepsilon_{tp}}{\varepsilon_f - \varepsilon_g} \tag{3}$$

Calibration points at 100% vapor and 100% liquid give two sets of f_{osc} and ε_{tp} data which, along with equations (1) and (2), can be used to calculate constants C_o and C_p associated with the capacitor sensor. It is desirable that the calibration points be taken as close as possible to the same temperatures to minimize temperature related changes of the capacitor sensor or other oscillator components. This calibration method is used due to the unique construction of the sensor that does not allow measurement of C_p directly. Since the frequency measurement technique depends mostly on the ability to precisely read the oscillator output, uncertainty in y associated with it is much smaller than the uncertainty related to the capacitor sensor geometry. Commercially available frequency meters are quite capable of deciphering a 10 Hz change (out of a total liquid to vapor frequency change of $6x10^4$Hz) near the oscillator's nominal $2.5x10^7$ Hz output.

METER IMPLEMENTATION

Most reported work pertaining to void fraction meters deals with closely controlled bench scale (or slightly larger) studies of flow characterization or studies of the meter accuracy. Fitting a void fraction meter to the near industrial environment of an existing Tevatron refrigerator requires design of unique mechanical features and definite size limitation. The resulting prototype design is shown in Fig. 3 installed in a section of "U–tube" used to connect refrigerator components. Flow is upward through the meter with the annular flow passage having identical cross sectional area as the nine meter long pipe rising from magnet string to refrigerator. Constant area helps to minimize flow acceleration and to preserve the flow pattern found in the pipe. Friction effects of the changing channel cross section upon the two fluid phases is small since, at the low mass velocity of ~57 kg/m^2s, pressure drop through the meter is calculated to be negligible. Significant measurement uncertainty for this configuration arises from the relatively wide annular flow space compared to other reported designs. The worst case ±4% occurs for void fractions of 50% in which vapor and liquid form concentric layers. Uncertainty tapers to smaller values at 0% and 100% void fraction.

Flow continues past the concentric tube capacitor sensor and then turns into the horizontal section of the U–tube. The flow turn allows for the entire meter assembly to be pulled at the Conflat flange out of its housing for inspection, repair, or calibration elsewhere. For the case of this U-tube installation, removal can only be done after the U–tube is removed from service and the insulating vacuum is broken. Ultimately, proposed installation in a valve box cryostat could easily accommodate meter removal, without breaking vacuum, by lengthening the G–10 thermal insulating section and intercepting this heat flow path with nitrogen cooling.

Electrically, both of the inner and outer capacitor sensor tubes are insulated from the U–tube due to significant voltage noise levels associated with the Tevatron magnets and found in much of the refrigerator equipment. The oscillator circuit resides inside the inner tube and this space is vented to the flow passage for safety and purification reasons. The oscillator is close to both capacitor tubes to reduce lead lengths (which contribute to the parasitic capacitance, C_p) and also to assure the oscillator a stable operating temperature (in this case very close to that of the flow). This central location is the only one that satisfies both of these requirements as well as allows for one piece removal of the meter from its housing. From the oscillator, the frequency signal exits the meter through a steel tube coiled for heat leak reduction. The same tube also connects to a warm pressure transducer (not shown) required to determine dielectric and density properties. A second tube contains wire leads for a carbon resistor temperature sensor used as a check to the pressure measurement and to monitor cooldown of the instrument.

For this prototype meter, data collection has been rather unsophisticated but very effective. After amplification of the frequency output and frequency division, the signal is read on a frequency meter. Pressure and temperature are read out on separate voltmeters. All three readings along with time are then recorded on video tape where "frame by frame" analysis can be performed if needed. Although data reduction beyond this point is cumbersome to say the least, large amounts of data may be stored for later review, the time relationship between pressure and frequency is preserved, and the frequency is recorded without the error of a difficult conversion to another format. A high accuracy frequency-to

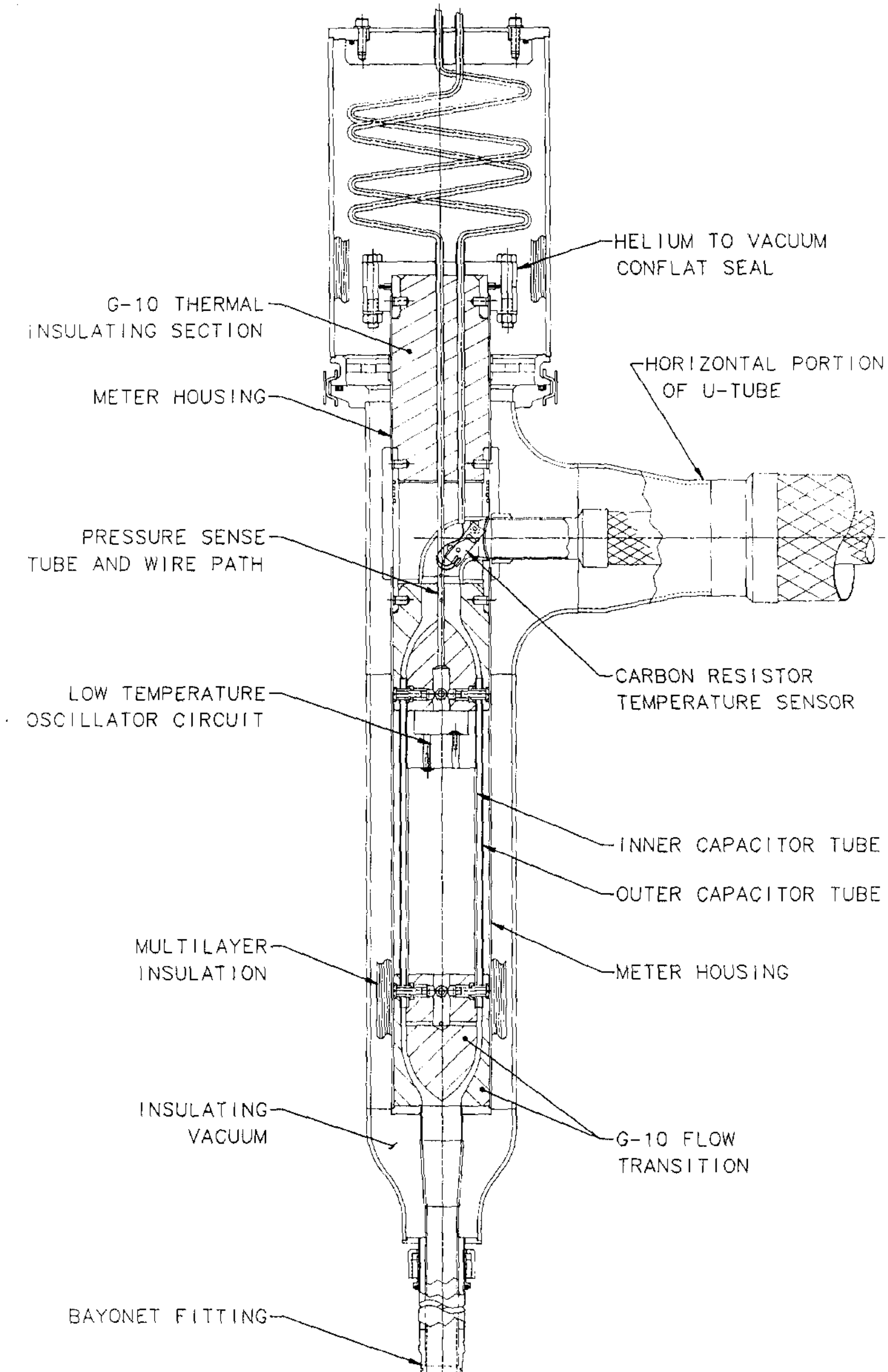

Fig. 3. Prototype void fraction meter installed in U-tube

voltage converter based on a phase lock loop circuit is planned which will allow the oscillator output to be fed to the existing accelerator control and data acquisition computer.

RESULTS

To evaluate the void fraction meter performance during changing flow patterns, the meter was first installed in a test refrigerator system. Instead of flowing to a magnet string, output from the wet expander entered an electrical heater (to provide refrigerator load), moved into a U shaped bend in which liquid could settle, and then rose vertically through the meter and back to the refrigerator. Typical data from this configuration is shown in Fig. 4. Oscillation in void fraction occurs as extended slugs of liquid, which collect in the bottom of the U-bend, are followed by peaks of two-phase flow. After the first two peaks of the figure, heater input increases 50% (to 150W) and remains constant for the next nine peaks. The oscillating characteristic continues, however, there is an increase in the average void fraction. The last peak represents a further increase in heater power.

The test system results indicate that dynamic trends can be closely followed by the meter. Fig. 4 also shows that the pressure at the meter fluctuates as the liquid slugs move past, a further indication of the presence of the oscillation. What is not precisely determined by the data is information such as slug volume or whether slugs are pure liquid. Uncertainty in these characteristics results from the finite (0.245m) sensing length of the meter. For instance, if slugs are less than this length, the meter necessarily reads some amount of void space, but if the slug itself has voids a similar reading could also be obtained.

The meter was next installed at a Tevatron satellite refrigerator in the position indicated in Fig. 1. The Joule-Thomson (J-T) valves (located at the end of each magnet string) were initially open to near the minimum positions known to allow stable refrigerator operation with unpowered magnets. After several hours of operation at these settings, each valve was closed by 1% in stem position (giving 7% flow area decrease for these equal percentage valves), thus initiating unstable operation. The plot of Fig. 5 shows the resulting measured void fraction. A second y axis is included on the graph to indicate the corresponding quality under the assumption of homogeneous flow.

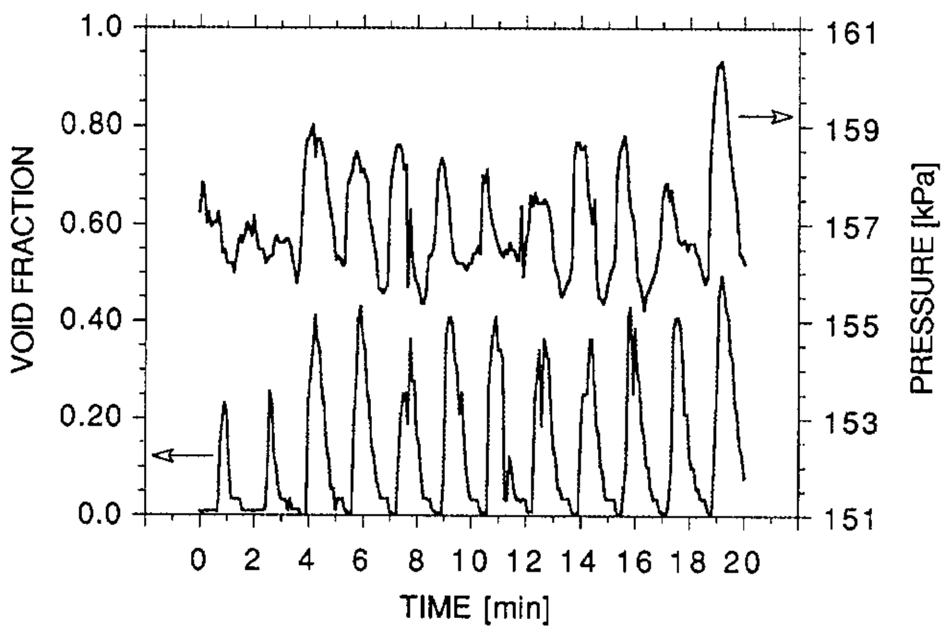

Fig. 4. Void fraction meter results from test refrigerator.

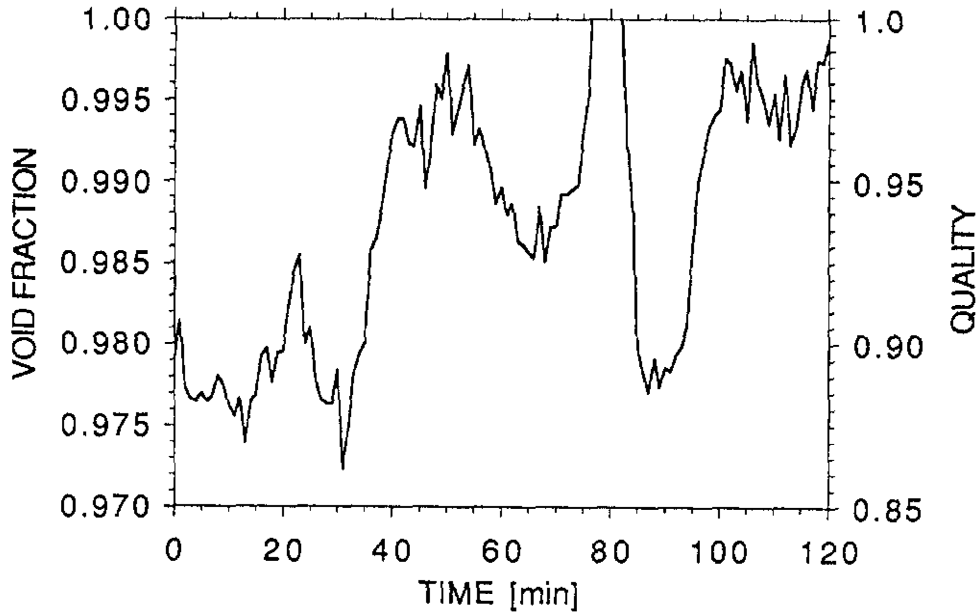

Fig. 5. Void fraction oscillation caused by flow reduction.

Referring to Fig. 5, the flow initially maintains a mean value about 97.8% void fraction (89% quality). Note this is a higher returning quality than the 80% thought required for stable powered magnet operation, but it is apparently sufficient (with some amount of instability indicated by small fluctuation) for the unpowered case. After 30 minutes the J-T valves incrementally close and void fraction steadily climbs over a ten minute period. An oscillation in void fraction then ensues, but there is no indication that large, purely liquid slugs pass the void fraction meter. Rather, the void fraction varies only between the steady state 97.8% and 100%, having a period on the order of that seen previously in Fig.2. Beyond 120 minutes (not shown) the flow at the meter becomes superheated. An oscillation in the meter output frequency persists during the superheat period due to the small variation in dielectric constant with the degree of superheat.

With further closing of the J-T valves, the two–phase to VPT pressure difference does start to oscillate (similar to Fig.2) but quickly becomes large because of the reduced flow. The fact that oscillation appears first at the meter and later at the magnets may be due to a mechanism affected by the actual difference in void fraction between the two locations at any given time. It is likely the difference in response is also enhanced by the greater sensitivity of the void fraction meter to two-phase disturbances. We can only speculate that liquid "slugging" in the magnet strings suggested by the data of Fig. 2 actually represents pockets of superheated vapor followed by two-phase flow, or that any liquid slugs formed become partially dispersed within the nine meter vertical pipe returning to the refrigerator.

A second test in the Tevatron refrigerator demonstrated the effect of powering magnets while maintaining insufficient helium flow. Magnet J-T valves were again adjusted to values sufficient for unpowered operation, and the system was allowed to settle. "Ramping" the magnets (i.e. cyclically powering magnets from 0 to 900 GeV, maintaining 900 GeV for a time, and then reducing power to 0 GeV and remaining unpowered for a time) was then initiated, resulting in increased heat load due to AC losses. Fig. 6 shows that the effect on flow void fraction is initial oscillation upon the start of ramping (at nine minutes in the figure), followed by a steady increase until the onset of superheated flow. Since the magnets are well upstream of the meter, they remain cold (and superconducting) for sometime, but would eventually warm up if flow was not increased to an appropriate level.

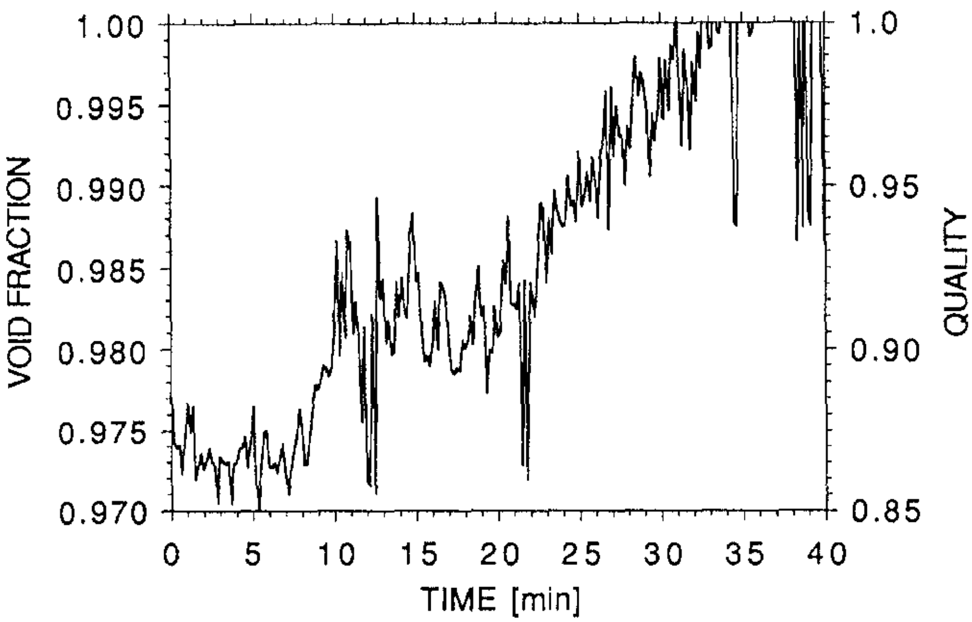

Fig. 6. Void fraction increase caused by turn on of magnet power.

CONCLUSION

A prototype void fraction meter was designed and constructed for use in a Tevatron satellite refrigerator. Data collected using the instrument support earlier suggestions that high void fraction flows in magnet strings (caused by reduced throughput or increased heat load) result in oscillation of void fraction with time. Insufficient data has been collected to fully characterize or explain marginally stable refrigerator operation. However, planned improvement in void fraction data acquisition along with full use of other existing instrumentation will allow more thorough analysis of the oscillatory behavior. The meter should prove useful for early detection of unstable refrigerator operation and refrigerator tuning, but these applications are hampered by physical limitations allowing only one meter for two magnet strings.

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