The Detection of Liquid Slugging Phenomena in Reciprocating Compressors via Power Measurements

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ABSTRACT

The presence of liquid refrigerant in the compressor cylinder during operation, or liquid slugging, is one of the most common causes of failure in reciprocating compressors. We propose to detect this fault by analyzing the electrical current flowing into the compressor and identifying the change in the load on the motor caused by the presence of liquid in the compressor cylinder. Two different types of liquid slugging are examined in this paper. In the first, small volumes of liquid are ingested during the steady-state operation of the compressor; in the second, small volumes of liquid are present at the suction port of the compressor immediately prior to the compressor start. Experimental data from a 1-ton split air conditioning system is used to demonstrate methods for identifying these faults.

1 INTRODUCTION

Vapor compression air conditioning equipment is susceptible to a wide variety of faults and failures. One particularly common fault is the ingestion of liquid refrigerant into the compressor cylinder from the suction port, otherwise known as liquid slugging. Under normal operating conditions, the refrigerant exiting the evaporator is 100% vapor, so that no liquid is present in the stream entering the compressor. Unfortunately, liquid refrigerant may accumulate at the suction port of the compressor for a variety of reasons. For example, a normal cooling load may not be sufficient to evaporate all of the refrigerant present in the condenser if the refrigerant loop contains an excessive mass of refrigerant, causing the liquid exiting the evaporator to be ingested by the compressor. Faulty components, such as a poorly tuned or broken expansion valve, can overfill the evaporator with refrigerant. Extreme conditions and transients can also result in liquid slugging because the refrigerant either will not completely evaporate in the evaporator or will recondense in the piping connecting the evaporator to the compressor. Liquid slugging is typically not noticed in such conditions because the air conditioning unit otherwise appears to be operating normally.

Compressors, and air conditioning systems in general, can be adversely affected in a variety of ways by liquid slugging. The mass flow rate into the compressor can be reduced as a result of liquid flashing in the compressor cylinder and at the valve plate (Afjei *et al.*, 1992). The ingestion of liquid refrigerant into the compressor shell and the subsequent boiling of refrigerant out of the lubrication oil can also reduce the lifetime of the compressor by causing damage to the motor winding insulation (Cunniffe *et al.*, 1986). The compressor lifetime may also be shortened by the increased stresses placed upon mechanical components, such as the crankshaft, valve plate, valves, pistons, and connecting rods, each time the piston collides with the incompressible liquid. While the reduction in compressor lifetime from these stresses might be gradual, large amounts of liquid have also been known to destroy compressors by snapping connecting rods and crankshafts. Cunniffe *et al.* (1986), Stouppe and Lau (1989), and Breuker and Braun (1998) all emphasize the prevalence of failures caused by liquid slugging in their surveys of common faults in rooftop air conditioning units (RTUs); in particular, Stouppe and Lau (1989) state that liquid slugging is the direct cause of 20% of the mechanical failures in the compressor. Moreover, reciprocating compressors, more than other types of compressors, have been shown to be particularly vulnerable to liquid slugging (Liu and Soedel, 1995).

Previous research into the causes and effects of liquid slugging provides important and useful background into the phenomenon. Singh *et al.* (1986a) appear to have published the first paper regarding liquid slugging, in which they present measurements showing that cylinder pressures during slugging conditions are up to 10 times higher than normal in a reciprocating compressor. Initial simulations were also performed to analytically explore the origins of these high pressures, and these simulations were further developed in Singh *et al.* (1986b), in which the simulated pressure waveforms had features closely resembling those observed in liquid slugging experiments. Simpson and Lis (1988) study the problem of reliably identifying liquid slugging phenomena by measuring forces on components in the compressor body, and conclude that the most reliable indicators are cylinder pressure and the force on the main bearing of the crankshaft. More recently, Shiva Prasad (2002) studied the analogous problem of liquid slugging in natural gas compressors with similar results.

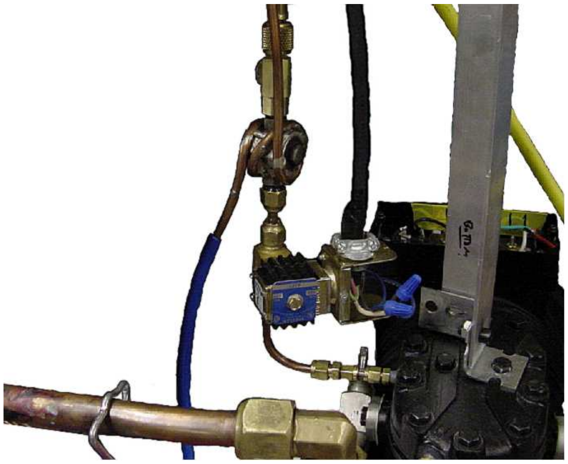
While it is clear from the extant fault surveys and the reports of liquid slugging experiments that liquid slugging can and does cause significant damage to reciprocating compressors, it is less obvious how to detect this phenomenon in a practical sense; one of the main points made by Simpson and Lis (1988), in fact, is that liquid slugging is not easily observed in an experimental setting because it is hard to reliably and repeatably measure the cylinder pressure or the stresses on compressor internals. An alternative method explored in this research is the detection of liquid slugging via analysis of the power flowing into the compressor motor. The sensor requirements for such a fault detection method are far less demanding because the electrical sensors can be mounted externally to the compressor, potentially making the method both less costly and more reliable.

Preliminary research into this method of liquid slugging detection was reported in Armstrong *et al.* (2006) . A semi-hermetic 3/4 hp compressor was used in those tests on a bench-top setup with the suction and discharge ports open to the ambient environment to evaluate the potential feasibility of detecting liquid slugging during the compressor startup as well as during steady-state operation. Variations in power that were correlated to the times of liquid injection were identified, suggesting that further investigation of such an approach might be fruitful. The research in this paper therefore builds upon the results of those early tests by evaluating the effects of liquid slugging on a 1-ton split system assembled in our laboratory.

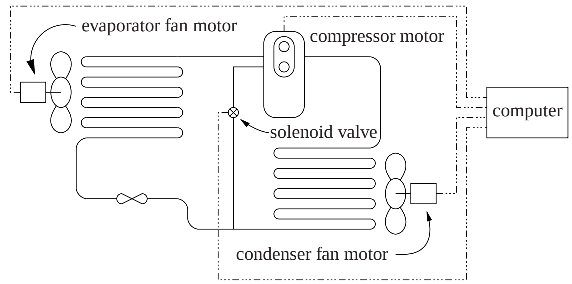
This paper will first discuss the experimental apparatus used to cause liquid slugging in the compressor, which incorporates modifications to the refrigerant loop as well as additional control circuitry. Two distinct types of liquid slugging will then be considered. The first of these types is that in which liquid refrigerant is ingested by the compressor during steady-state operation; this will be referred to as *steady-state slugging*. The second type of slugging is that in which liquid refrigerant is either pooled directly on the valve plate above the compressor cylinder or in the cylinder itself immediately prior to startup, so that it is pulled into the cylinder when the compressor turns on. This type of liquid slugging will be referred to as *transient liquid slugging.* Detailed discussion and experimental results for each type of liquid slugging will be given in their own respective sections.

2 EXPERIMENTAL APPARATUS

The split system used as a test bed for these experiments was manufactured by International Comfort Products, and has a cooling capacity of 1 ton and a refrigerant capacity of 96 ounces (about 3000mL) of R-22. A two-cylinder semi-hermetic reciprocating compressor was installed for testing purposes, and the resulting air-conditioning system was modified in a manner illustrated schematically in Figure 1b. The use of a semi-hermetic compressor made it possible to modify the compressor head by adding the liquid injection apparatus, pictured in Figure 1a, so that liquid refrigerant could be injected directly into the cylinder. The additional refrigerant line was plumbed directly into the side of the compressor head with a short stub of stainless steel tubing, so that the refrigerant could be deposited directly above the suction valve. As can be seen from the picture, a sight glass and a solenoid valve were also installed in the liquid-injection line; the sight glass was installed to visually ascertain the amount of refrigerant being injected into the cylinder, while the solenoid valve was installed to precisely control the timing and size of the liquid slugs that were injected. The precise quality of the mixture entering the compressor head is unknown, as is the duration of time during which the mixture is present in the compressor, because some of the liquid will evaporate as it enters the compressor head. The amount of liquid entering the compressor head can be specified arbitrarily, however, ensuring



(a) Picture of the automated liquid injection apparatus. The refrigerant line directly into the compressor head, including the solenoid valve and sight glass, is visible; an extra copper pipe was soldered to the sight glass through which cold water was circulated to condense the refrigerant.



(b) Diagram of the experimental RTU platform with its accompanying control system. The dashed lines signify the connections between the computer and the individual loads which it controls.

Figure 1: Schematic and photograph of the experimental apparatus, illustrating the construction of the unit as well as modifications made to study liquid slugging phenomena.

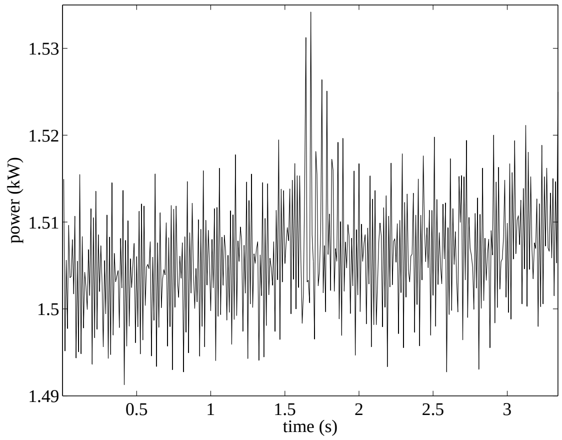
that the quantity of liquid injected into the cylinder is less than or equal to the programmed volume.

The solenoid valve was controlled by a microcontroller-based control board. This control board was designed to turn the fans, compressor, and the solenoid on and off in pre-programmed time sequences of the test operator's choosing. Complicated test protocols could thus be run for extended periods of time without continuous supervision. This control system was designed to synchronize load-switching operations with the electric utility, enabling the loads to be turned on at specific points in the line cycle. The computer which managed the control board, a 1.8 GHz off-the-shelf PC running Linux, was also outfitted with a multi-channel, 8 kHz per channel USB-based data acquisition system; this allowed the control and data acquisition functions to be coordinated from the same terminal.

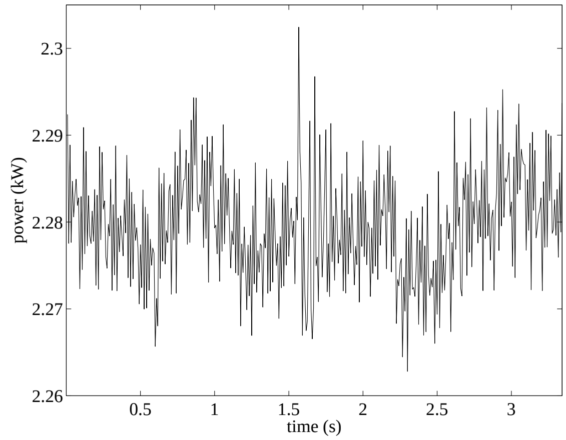
3 STEADY-STATE LIQUID SLUGGING

The dynamic behavior of the compressor motor under normal operating conditions is governed by a number of factors. The load on the piston caused by the state of the refrigerant in the cylinder is of primary importance to the method of identifying liquid slugging by electrical measurements, because the forces generated when the piston acts on a liquid-vapor mixture are far greater than those generated in compressing vapor. The brief change in the mechanical load on the compressor motor when liquid is present in the cylinder, until the liquid either evaporates or is pushed out of the discharge port, will manifest itself in the motor electrical load. Changing cooling load at the evaporator or ambient conditions at the condenser can also affect the motor electrical load through related changes in the suction and discharge pressures. Similarly, the total mass of refrigerant present in the system can have an effect on the load on the piston. Electrical parameters of the motor, such as the stator and rotor impedances, also have a significant effect on the power consumed by the motor; these impedances can change due to thermal phenomena acting over the compressor's operating cycle, or with normal degradation or faults acting over the compressor's lifetime.

Consideration of the differing time scales over which the aforementioned phenomena change the motor's behavior is extremely important in developing a diagnostic indicator for liquid slugging. For example, environmental conditions change relatively slowly, over the course of minutes or hours. Similarly, motor windings gradually heat up after the compressor is turned on, approaching their final temperature after 30 minutes or so. In comparison, changes in compressor power caused by liquid slugging occur on a much shorter timescale, taking place over only a few seconds because of the rapid exit of the refrigerant from the cylinder. The proposed method for identifying steady-



(a) Plot of the real power estimate for the compressor during a liquid slugging event for the compressor current sensor.



(b) Plot of the real power estimate for the compressor during a liquid slugging event for the aggregate current sensor.

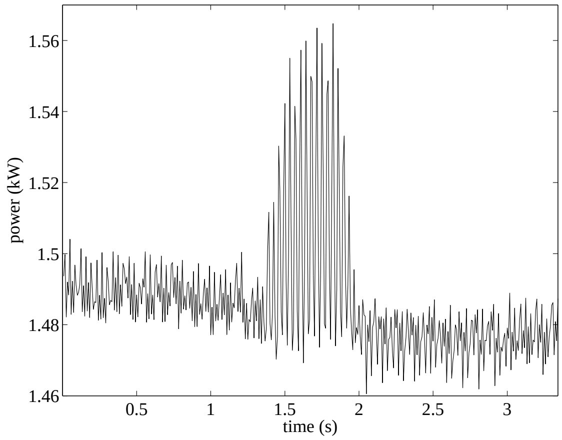
Figure 2: Comparison of the compressor-only and the aggregate power sensors; 0.68 mL of liquid refrigerant was injected during this test. The average power is higher in Figure 2b because the sensor is monitoring the compressor as well as the condenser and evaporator fans.

state liquid slugging exploits these time scale differences by looking for extremely brief surges in the power flowing into the compressor. This approach does not require calibration for cooling load, ambient environmental conditions, or even refrigerant charge, because changes in these quantities will occur over time scales that are not relevant to the identification problem. Moreover, should there be any abrupt changes in the compressor power that were not related to liquid slugging, these would also be of interest because they would relate to other significant faults in the RTU.

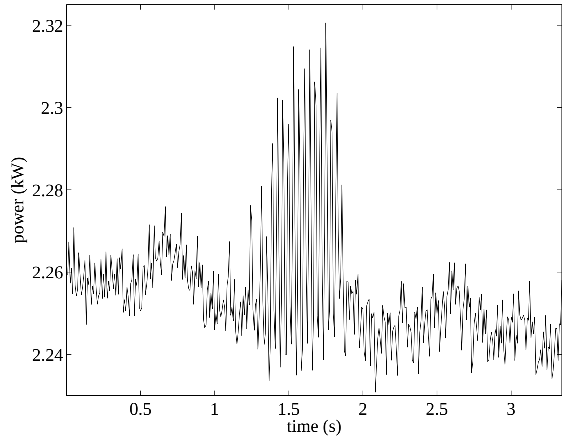
Power flowing into the compressor can be observed from multiple locations in a conventionally wired RTU. Power transducers placed directly on the wires feeding the compressor yield observations of the power which can be used to perform the desired diagnostics. Alternatively, the power transducers may be installed at the electrical service entrance for the purpose of observing all of the electrical loads internal to the RTU, e.g., the evaporator and condenser fans as well as the compressor. Such observations of the aggregate power have two potential benefits: a reduction in the number of power transducers needed and the possibility of developing diagnostic procedures for any or all of the electrical loads contained in the RTU. While the complexity of analyzing an aggregate power signal is greater than that of a dedicated power signal, the potential for reduced sensor cost and increased reliability for a given set of information provides a strong motivation for developing liquid slugging diagnostics for both dedicated and aggregate power measurements.

The particular method used to estimate the power consumption employs measurements of the current supplied, either to the compressor alone or of the aggregate unit, to obtain estimates of the real power; this method is described in detail in Leeb *et al.* (1995). These estimates are typically called “spectral envelope estimates” because each sample of the power estimate is generated by computing the short-time Fourier transform of a sliding window of data. Spectral envelope estimates often prove useful in the analysis of power signatures because they effectively remove the 60 Hz component from the current waveform, providing a means of identifying the shape of the underlying power transient, which can be used for load identification or diagnostic purposes (Laughman *et al.*, 2003). The spectral envelope estimates used in this research were sampled at 120 Hz.

An experimental protocol was devised to characterize the effect of steady-state liquid slugging on the compressor power. While the effects of compressor faults other than liquid slugging on the compressor power must eventually be considered, the only type of fault studied during these experiments was liquid slugging. Before conducting any tests, the compressor was run for an extended period of time to bring the motor windings to their final operating temperature, so that any potential variation in the experiments could be eliminated. Although this was not strictly necessary because the time scale of interest was much shorter than the thermal transients, this step was included so that every reasonable



(a) Plot of the real power estimate for the compressor during a liquid slugging event for the compressor current sensor.



(b) Plot of the real power estimate for the compressor during a liquid slugging event for the aggregate current sensor.

Figure 3: Comparison of the compressor-only and the aggregate power sensors. 8.5 mL of liquid refrigerant was injected during this test.

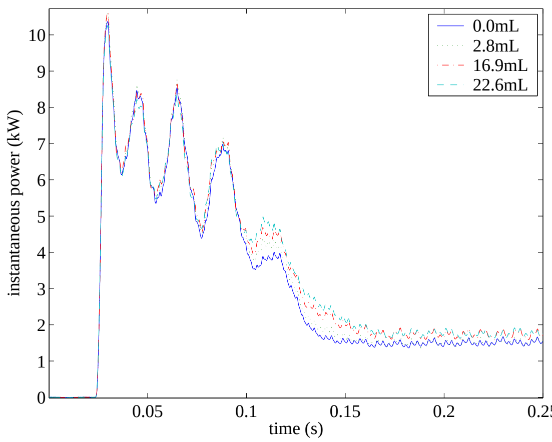
precaution was taken.

Trials were conducted in which the compressor was run for an extended period of time, during which the solenoid valve was periodically opened for precisely controlled time intervals to let repeatable volumes of liquid refrigerant into the compressor. Observations of the estimates of compressor power over this time period show that the compressor power does indeed reflect a change in the load on the compressor motor, as can be seen in Figures 2 and 3. These figures illustrate the estimates of the real power consumed only by the compressor (Figures 2a and 3a) and by the aggregate collection of loads in the RTU (Figures 2b and 3b) over the time interval during which the compressor ingested the liquid slug.

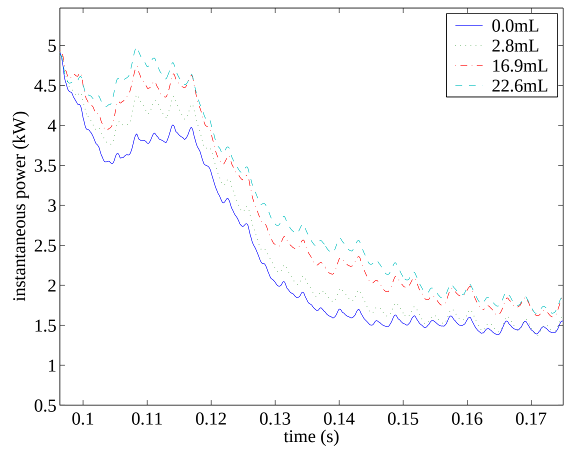
It is clear from these figures that liquid slugs have an effect on the estimates of compressor power which are observable from both the dedicated and aggregate current sensors. An extremely small liquid slug of 0.68 mL is ingested in the data illustrated in Figure 2. The effect of the liquid slug on the compressor power estimate is apparent in Figure 2a, as it causes a spike that is approximately 2% greater than the average value of the waveform. While this spike is also visible in the estimate of the aggregate power illustrated in Figure 2b, the large amount of variation in the power estimate due to the fan motors makes this feature difficult to differentiate from the background noise. In comparison, a slug of approximately 8.5 mL of liquid is much easier to identify in both the compressor and aggregate spectral envelope estimates of Figure 3. The series of spikes evident in the compressor power estimate plotted in Figure 3a represent an abrupt 5% jump in the compressor spectral envelope waveform, and the analogous series of spikes in the aggregate power estimate plotted in Figure 3b equate to a similarly rapid 2.5% jump. The ease with which these changes can be detected with the eye suggests that a fault detection method could be developed to track and log the number of times that liquid slugs are ingested by the compressor, as well as the approximate volume of liquid contained in these slugs. One useful algorithm for detecting this type of fault is described in Armstrong *et al.* (2006).

4 TRANSIENT LIQUID SLUGGING

Many characteristics of the transient liquid slugging phenomenon are similar to those of steady-state liquid slugging, but there are some important differences. The first of these differences involves the time at which liquid refrigerant enters the compressor cylinder. While the liquid refrigerant always enters the cylinder through the suction valve during steady-state liquid slugging, the liquid refrigerant may be present in the cylinder prior to startup in the case of transient liquid slugging. This circumstance may occur because the refrigerant vapor present in the cylinder can be cooled to the point of condensation when the compressor is off. The refrigerant vapor may also have condensed in the refrigerant



(a) Averaged instantaneous three phase power flowing into the compressor during startup for transient liquid slugs of increasing size as monitored by the compressor current sensors. Notice that the main difference occurs at the tail end of the startup transient.



(b) Zoomed in plot of the averaged instantaneous power waveforms to highlight the changes caused by transient liquid slugs of increasing size.

Figure 4: Averaged plots of the three phase instantaneous power during the compressor startup transient. Each waveform is the average of a set of approximately 30 startup transients with a transient liquid slug of a particular size; the sizes of the slugs are given in the legend of the plot. The instantaneous power waveform is sampled at 8 kHz.

piping near the suction port, or in the cylinder head, causing the liquid refrigerant to be immediately ingested by the compressor during the subsequent start. The quantity of liquid ingested in such circumstances can potentially be quite large because it is only limited by the volume of the cylinder and the associated piping.

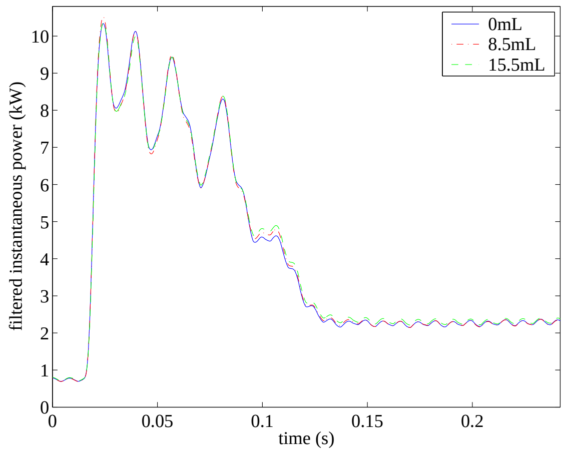
As in the case of steady-state liquid slugging, it is essential to understand the factors that govern the shape of the compressor startup power transient when seeking to quantify the effect that transient liquid slugging has on that startup transient. Many of the behaviors that affect steady-state liquid slugging also affect transient liquid slugging; these include the refrigerant charge, motor impedance, and environmental conditions. Additional factors that influence the shape of the startup transient include the acceleration of the motor shaft, the electrical angle when the motor is started, and the initial position of the pistons.

In order to ascertain whether or not liquid slugging can be identified from observations either of the compressor power or of the aggregate power flowing into the entire RTU, the experiments were conducted in a manner that eliminated or reduced the effect of as many of these variations as possible. Most of the sources of variation (the winding impedance, the initial electrical angle, and the refrigerant charge) were mitigated by carefully designing the experimental protocol and constructing the experimental apparatus. Because the variation caused by the initial position of the piston could not be similarly eliminated, the piston position was characterized by collecting a number of compressor start transients and observing the average behavior of a given set of transients.

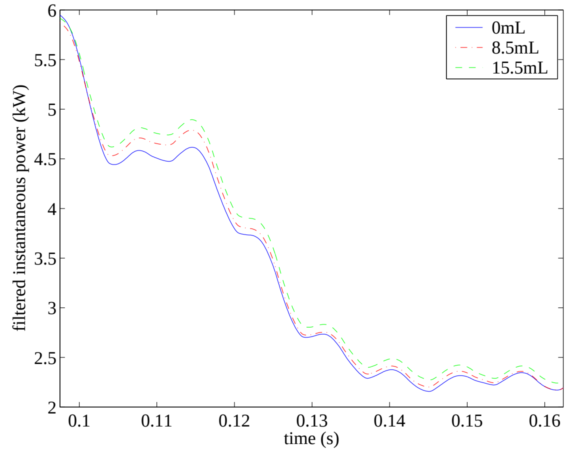
Rather than using the spectral envelope estimates as were used for the steady-state liquid slugging detection, the three phase instantaneous power was computed for each transient start to reduce the effect of the electrical angle on the diagnostic indicator. Equation 1 specifies the computation of this instantaneous power signal $P_i[k]$ at each sample point k for the currents flowing into the compressor and the corresponding line-to-neutral referenced voltages. This preprocessing step was performed because the instantaneous power signal retains the DC component of the power signal, thereby eliminating the components of the signal related to the phase dependence of the set of voltage waveforms.

$$V_{an}[k]I_a[k] + V_{bn}[k]I_b[k] + V_{cn}[k]I_c[k] = P_i[k] \tag{1}$$

The particular mode of transient liquid slugging investigated during these experiments was that in which the liquid refrigerant was pooled on the valve plate directly above the suction valve. The experimental procedures that simulated this fault mode were performed by opening the solenoid valve for a specified interval of time, after which the compres-



(a) Filtered plots of the averaged instantaneous three phase power flowing into the electrical service of the RTU for transient liquid slugs of increasing size as monitored by the aggregate current sensor. The difference at the tail of the startup transients is also visible in these waveforms.



(b) Zoomed in plot of the filtered averaged instantaneous power waveforms, highlighting the changes caused by the transient liquid slugging events.

Figure 5: Filtered plots of the averaged instantaneous three phase power during the compressor startup transient while the fans were in operation, as observed from the electrical service entrance of the RTU. Each waveform is the average of a set of approximately 30 startup transients with a liquid slug of the size indicated in the legend of the plot. The instantaneous power waveform is sampled at 8 kHz.

sor was immediately started; the compressor must be started quickly to pull the injected refrigerant into the cylinder before it evaporates in the cylinder head. As in the steady-state liquid slugging tests, the compressor was operated for a substantial interval of time before conducting these tests, so that the motor windings reached their final temperature. Furthermore, a series of different experiments were conducted and in each experiment a different volume of liquid was injected, so that the effect of different amounts of liquid on the instantaneous power transient could be studied.

Experimental results show that transient liquid slugging has a visible effect on the compressor power startup transient monitored from the compressor power sensors, as seen in Figure 4. Figure 4a illustrates a set of plots of the means of the instantaneous power for a range of different volumes of ingested liquid. For example, the trace denoted by the solid line in the legend illustrates the mean of 32 instantaneous power transients when there is no liquid injected, while the trace denoted by the dashed line in the legend similarly illustrates the mean of 30 instantaneous power transients when 22.6 mL of liquid are injected into the cylinder. A comparison of these plots shows that, while there is little difference between the traces at the beginning of the power transients, there are noticeable changes in the shape of the transient for differing amounts of liquid. This particular section of the plot that manifests this difference is magnified in Figure 4b, in which larger volumes of liquid are seen to correspond to larger deviations from the “no-slugging” transient. The amount of power consumed during these periods of deviation during a liquid slug are up to 50% greater than the amount of power consumed when no liquid is present in the compressor head; this suggests that an automatic detection method could be designed to identify the presence of transient liquid slugging.

Figure 5 illustrates analogous behavior that can also be observed in the aggregate power waveforms. To effectively depict these differences, it was necessary to apply a mean-smoothing filter to the aggregate instantaneous power waveform in order to damp oscillations in instantanteous power caused by the power consumption of the line-to-line connected fans. The average of the mean-smoothed instantaneous power traces for a number of different volumes of liquid slugs are displayed in Figure 5a. These plots look similar to those in Figure 4 in that transient liquid slugs have the same effect on the compressor startup transients observed in the aggregate instantaneous power waveforms as they do on the startup transients observed in the dedicated compressor instantaneous power waveforms. The magnified tail end of these waveforms is also illustrated in Figure 5b; it is clear from this plot that the transient liquid slugging can also be observed in the aggregate instantaneous power waveform.

5 DISCUSSION

The results presented in this paper show that even small (less than damaging) ingested amounts of liquid can be identified by simple, reliable, non-instrusive electrical measurements of the power flowing into the compressor. Furthermore, liquid slugging can be detected from measurements of the aggregate current flowing into the collection of electrical loads in the RTU, as well as measurements of the compressor current alone. These results were demonstrated on a semi-hermetic reciprocating compressor, which was connected to a commercially available condenser and evaporator, providing further evidence that such a diagnostic procedure could be feasible in a commercial or residential setting.

While this diagnostic could conceivably be incorporated into a fault detection and diagnostic system for RTUs, additional research into developing robust fault detection methods and extensive field tests are necessary to insure that these fault detection methods could produce reliable results in the field. Work is presently being conducted at MIT to continue developing these and related diagnostics.

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