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X-RAY INVESTIGATION OF AN UPRIGHT FREEZER AT VARIOUS AMBIENT TEMPERATURES

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ABSTRACT

In this study, the x-ray system is used as an observation tool for refrigerant movements in a domestic refrigerator. It is intended to show researchers what is happening inside the tubes when we plug in the refrigerator. The effect of ambient temperature is included to investigate the response of the system. During the experimental studies, ambient temperature is held at 12, 24, and 43 °C with ±2°C stability. The start-up period is investigated in details. By matching the real time videos with the temperature data, comments are made. The studies are made on a two-door upright freezer having 435 liters volume, and automatic defrost feature. Refrigerant is R134a. Real time x-ray images and system temperatures are recorded during experiments. X-ray video images are recorded during the pull-down (cooling down of the refrigerator from ambient temperature) and cyclic periods as well. The special interest is shown to dryer, capillary exit, evaporator inlet, and accumulator regions. By matching the video images and temperature data, the flow regimes, charge inventory, accumulator functioning, and the changes of subcooling degree at the dryer inlet are explained. Possible flow induced noise mechanisms are pointed out.

INTRODUCTION

The thermal system design procedure of a domestic refrigerator consists of both obtaining the targeted energy consumption at competitive cost levels, and fulfilling the thermal performance criteria for various climate conditions. While the thermal performance is a natural requirement for a refrigerator, the customer satisfaction and competition require more detailed studies to make faster achievements to set temperatures, and less noise levels at steady state and transient periods as well. Therefore, some transients, which occur on the start-up and cycling periods, may be interesting and important. The situations, related to dynamic behavior, require greater interest and careful design considerations especially when noise, charge inventory, energy consumption, and accumulator volume are point of interest. Some of the most important transients are refrigerant migration during off-cycle and charge redistribution during on-cycle. The effect of hot gas migration from condenser to evaporator during off period was investigated by Krause & Bullard [1], Coulter & Bullard [2] and Rubas & Bullard [3]. They found that the migration during the off-cycle could cause increase of cabinet load by 2 to 6 %. During the first minute of the on-cycle, when the refrigerant is being redistributed from the evaporator to the oil sump, 2 to 3.3 % of the capacity is lost and the power demand may increase by as much as 1.7 %. After the first minute of on-cycle, while some refrigerant is being redistributed back into the evaporator, there is up to a 3% capacity loss. Besides of thermal transients the issues of noise problems are also investigated. Rodarte et al. [4,5] investigated noise generation mechanisms caused by expansion devices. In the study, flow through the capillary tube is also studied. The velocity and quality of refrigerant, the penetration length and location of capillary exit tube in the evaporator are found as important factors affecting the noise characteristics. Besides of academic studies, most people know some characteristic noises coming from their refrigerator. “Hissing” noise in the beginning of an off-cycle and the “popping” and “boiling like” noises at the beginning of on-cycle are the most common ones.

In this study, an x-ray imaging facility is extensively used. In order to understand the dynamic behavior of a refrigerator, charge movements and temperature changes are observed simultaneously. Whole refrigerator is located in the x-ray cabinet and experiments are conducted by taking real time video records of the x-ray images. The results are found very interesting. X-ray observations are used to explain some changes on temperature curves. Figures and photos are given. It is expected that the observations made in this study will give some useful insights to researchers, and will help engineers for better understanding of common transients of refrigerator.

EXPERIMENTAL STUDY

Measurement Equipment

X-ray unit: The x-ray system is Feinfocus FXS-160. It is a real time x-ray unit with a micro focus capability. The micro focusing feature adds more resolution comparing to classical systems. This helps taking good pictures for both large units such as refrigerators and small units like integrated circuits. During the x–ray process it is possible to take real time video records and snapshot pictures together. The maximum capacity of the probe is 160kV. The maximum conditions can be chosen at either 160kV-1mA or 50 kV-3 mA. The best results achieved in the refrigerator study are 80-120 kV and 0.1-0.3 mA values. The x-ray unit's chamber temperature can be set between 10-45°C with accuracy of ±2°C. All chamber walls are made of 5 mm thick lead plates plus 50 mm thermal insulation. Only liquid phase is identifiable when vapor and liquid phases are present together on the x-ray monitor. It is not studied to see if there is any difference in image quality for different refrigerants like R12, R600a etc. It can be expected to have difficulties for less denser refrigerants like R600a. Copper sections like dryer, capillary exit adaptor, and accumulator inlet tube are seen darker while the alluminum (Al) evaporator tubes and accumulator are seen lighter (clearer) colors. It is obvious that low density materials like Al is better for x-ray studies. Therefore, the flow in the steel condenser tubes can not be seen. Figure 1. Shows a sketch of the x-ray unit.

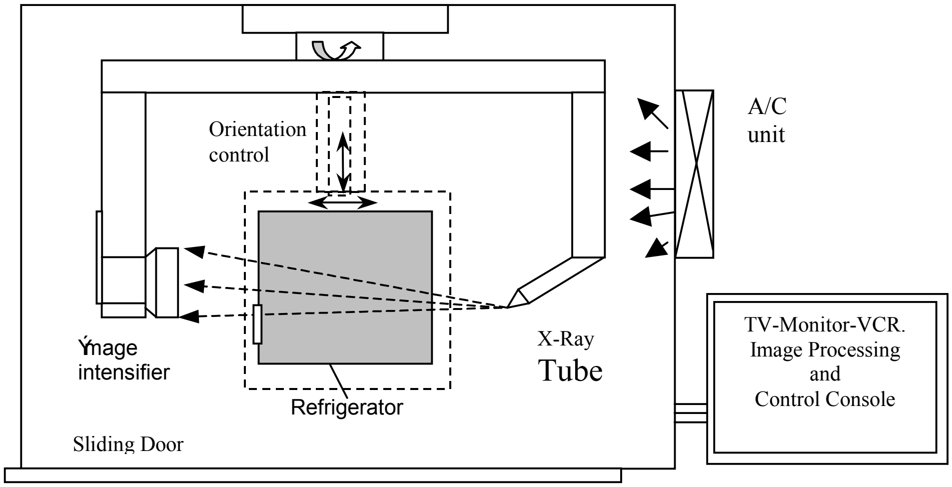

Figure 1: Schematic view of x-ray system

Refrigerator description: A two-door upright freezer type refrigerator with 435 l total volume is used for experimental study. Refrigerant is R134a, dryer is molecular sieve type, and capillary tube is 0.8 mm ID. Compressor has 180 W cooling capacity. The insulation is polyurethane with c-penthane blowing agent. The average thickness of polyurethane on the freezer and refrigerator compartment walls are 70 mm, and 50 mm respectively. The order of the components on the circuit is given in Fig. 2-a. The locations where the x-ray investigation is focused are highlighted in the Fig. 2-a, too.

Sensors: Temperature measurements are made with T type 24 grade thermocouples (T/C) attached to different locations on the whole cooling circuit. The most important ones are given in Fig. 2-b. All T/C leads are insulated with a piece of Styrofoam to measure surface temperatures having less affected from the surround. Temperatures are measured from the tube surface for easy instrumentation. The real refrigerant temperatures may differ significantly especially in transient periods like start-up [3,6].

Data Acquisition: Temperature data is recorded by use of a 20 channel data logger. Scanning interval is chosen as 15 seconds. T/C calibrations are made by use of reference thermometer and a constant temperature bath.

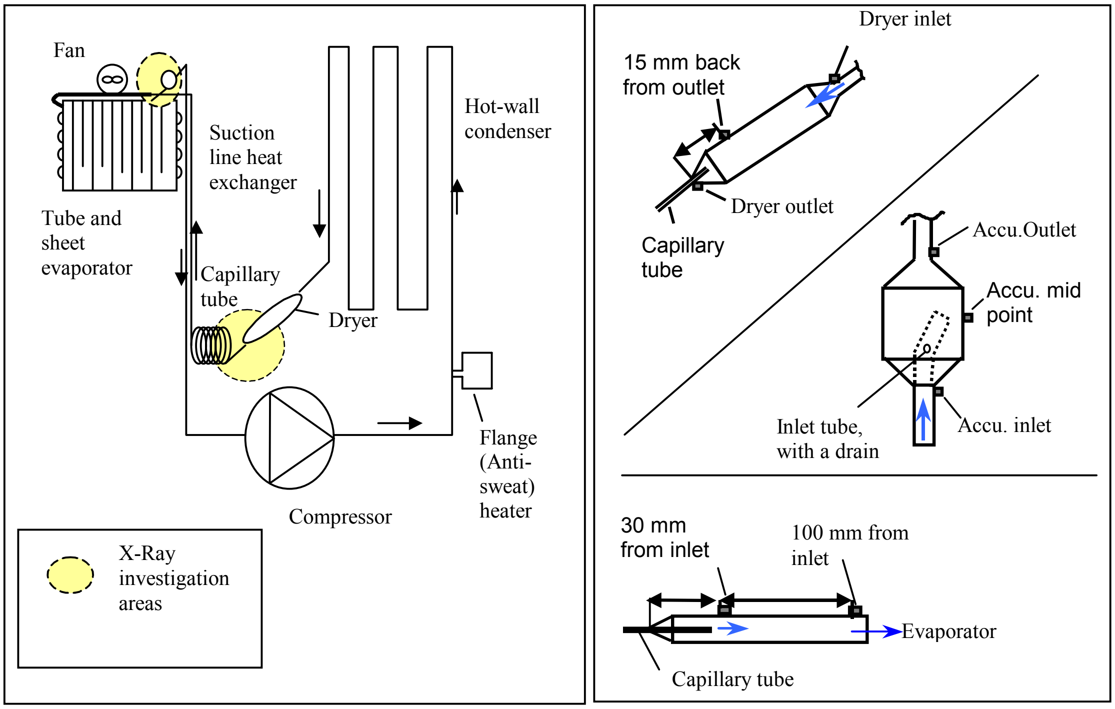

Figure 2: a) Refrigerator cooling circuit, b) T/C placements on the cooling system

Experimental Procedure

The refrigerator is placed in the x-ray chamber where ambient temperature is controlled. Ambient temperatures are choosen as 12°C, 24°C, and 43°C (stability ±2°C) to cover operation range of the selected refrigerator. The refrigerator is left in rest position with doors are fully open for at least 12 hours for temperature stabilization. Temperature data collection and video recording are started before the refrigerator is plugged in. Some orientation control tests are made to get best view and image quality from the interested locations. During the test, by locating the x-ray probe to specific sections shown in Fig. 2-a, images are recorded and monitored as well. Position changes when refrigerator is moved back and forth or turned on the platform may cause vibration that alters the transients and makes difficult to find exactly the same position back again for further comparisons. In order to keep the x-ray probe in a specific location during the test without any movement, two identical experiments are made for the same ambient temperature. In the first test, the probe is located to evaporator inlet and accumulator section together, and in the second test to dryer section only. After the tests are completed, temperature and video records are investigated together. Temperature curves are compared with x-ray data on time basis. Thus, the temperature changes and refrigerant movements are explained together. Video records present opportunity of watching questionable situations again and again. The study mainly focused on dryer, capillary outlet - evaporator inlet, and accumulator sections (Fig. 2-a).

RESULTS AND DISCUSSION

By focusing on the start-up section, the following figures are obtained. Figure 3-a shows the evaporator inlet and accumulator inlet temperatures for three different ambient conditions. It should be keep in mind that the temperatures are measured form the tube surfaces. Regardless of the ambient conditions, the evaporator inlet temperatures make sharp decrease at the beginning and start increasing for some time and decrease again. The explanations of these behaviors are made by the help of x-ray observations given in Table 1 to 3, and Figure 4 to 8. In the beginning, the capillary puts more resistance to flow while the entrance is mostly in vapor phase. During this time, the inflow is much less than the out flow in the evaporator, which causes rapid evacuation of evaporator. Therefore evaporation pressure and temperature decreases together. After that period, both due to increase on subcool, and condenser pressure build-up, flowrate through the capillary tube increases [6,7,8]. On the other hand the cabinet temperatures are still close to ambient temperature. Result is higher load on evaporator, which increases evaporation temperature. This situation continues until a peak value is achieved. Then, it starts decreasing while the cabinet air continuously cools down. After this region the cabinet temperature drives the evaporator temperature (Fig. 3-a).

When the accumulator inlet temperature equalizes with the evaporator inlet temperature, it means the liquid refrigerant reaches to accumulator (Fig. 3-a). This is a proof of completely wetted evaporator. The time for the complete wetness is longer for decreasing ambient temperature. This feature is expected because, at lower ambient temperatures more charge stays in the condenser side, and as evaporation temperature is lower the flow rate is smaller. Lower flowrate and accumulation on condenser side cause delay on the charge distribution from condenser to evaporator. The points are marked as A, B and C in Figure 3-a as a proof of liquid arrival to accumulator.

Unlike the others, a very interesting phenomenon occurs at 43 °C. Evaporator and accumulator temperatures fluctuate between –9 °C and –18 °C for 45 minutes after 16 minutes from start-up, where the subcool is approaching to its second peak value. The fluctuations on the evaporator temperature at 43 °C ambient could not be explained completely. It may be due to unsteadiness on the capillary inlet conditions, or dynamics of the capillary and suction line heat exchanger effect on flow. It is not a common behavior for other refrigerator models, therefore the circuiting should be considered as a possible reason, too.

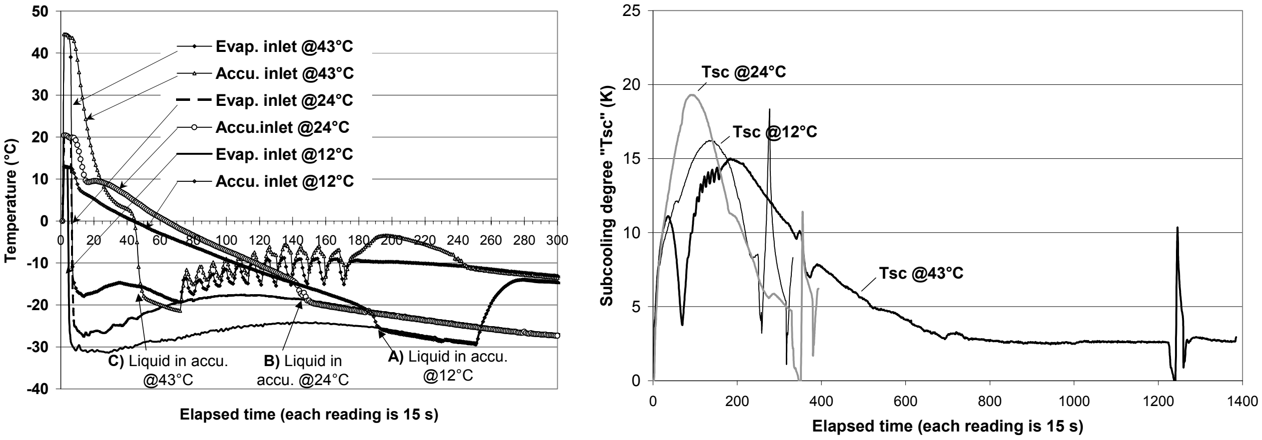

Figure 3: a) Evaporator and accumulator temperature changes during first 75 min. after start-up.
b) Subcooling degree (Tsc) change during almost 6 hours after start-up

Subcooling degree (Tsc) at the capillary tube inlet is calculated by simply subtracting the dryer exit temperature form the condensation temperature. Change of Tsc with time is shown in Fig. 3-b. The general characteristics of the curves are quite different. For 43 °C ambient temperature the curve increases first to 11 K, after that it decreases to 4 K then it makes a peak at 15 K again and finally starts decreasing to a steady state value of 2.5 K. For other ambient temperatures the curves are similar, first makes a peak and decrease continuously until compressor stops. The amplitude of peak value of subcooling is not parallel to ambient temperature. The highest peak of 18 K is obtained at 24 °C ambient, instead of 12 °C ambient temperature. This unexpected behavior can be explained with the alignment of condenser tubes before the dryer. As it is shown in Fig. 2-a, the condenser tubes are vertical, therefore it is possible that some of the refrigerant may condense and accumulate in previous tube bends at lower ambient temperatures. That may result lower subcooling degrees at the capillary inlet. From Fig 3-b it is also observed that the subcooling makes a very sharp peak when the compressor stops. It is due to the additional cooling effect when all liquid migrates to evaporator, for some time the dryer inner surfaces and the granules become wet therefore the evaporative cooling causes very sharp decrease on dryer exit temperature. Then it approaches to zero while all temperature on condenser side equalizes to ambient temperature with remained refrigerant vapor.

Besides of above explanations, the results of the x-ray observations and temperature measurements are given in Table 1 to 3, and Figure 4 to 8. In order to share the results in an appropriate format, the notices are summarized in a column format so that comparisons for different ambient temperatures can be made easily. Some links to temperature measurements and to characteristic photographs are also made in the table.

Table 1 Some important notices from X-Ray observations (Evaporator and Accumulator section, first 3 hr)

Tamb= 12°C	**Tamb= 24 °C**	**Tamb=43°C**
T_{evap} decreases to –32°C in 15-30 s.	T_{evap} decreases to –25°C in 45 s	Right after the start-up some flow is observed in the evaporator tubes. Tevap decreases to –17°C in 60 seconds.
The flow in evaporator tubes right after the capillary is visible as thin layer @ 7th minute.	The flow in evaporator tubes right after the capillary is visible as thin layer @ 7th minute.	Temp. starts increasing to –15 °C ., then decrease slightly.
	Flow regime is stratified - intermittent in the evaporator tube @ 8-12 min.	The flow regime is stratified - intermittent in the evaporator tube @ 8-14 min.
	After sharp decrease in T_{evap} it makes a peak –17°C at 23rd min.	During the 45 min. of duration T_{evap} and T_{accu} fluctuates between –9°C and –18°C. The reason of this behavior cannot be explained.
The first liquid is observed in the accumulator @48th min. **(Fig. 3-a)**	The first liquid is observed in the accumulator @39th min. **(Fig. 3-a, Fig. 4)**	The first liquid is observed @14th. Min. **(Fig. 3-a)**
	The liquid level in the accu. is increasing @42nd min.	The liquid level increases until 29th minute when it reaches max. level. Then it starts decreasing again. (Fig 3-a). The accumulator is almost empty, little amount of either refrigerant or oil is visible @57th min. **(Fig . 3-b)**
The liq. Level in the accu. Is max. @ 1 h 06 min.	The liq. level in the accu. is max. @ 1 h 25 min. **(Fig. 4)**	The liq. Level in the accumulator starts increasing again @1:06:00. Half full @2:14:00. Maximum @3:20:00, stays at this level. **(Fig. 3-b)**

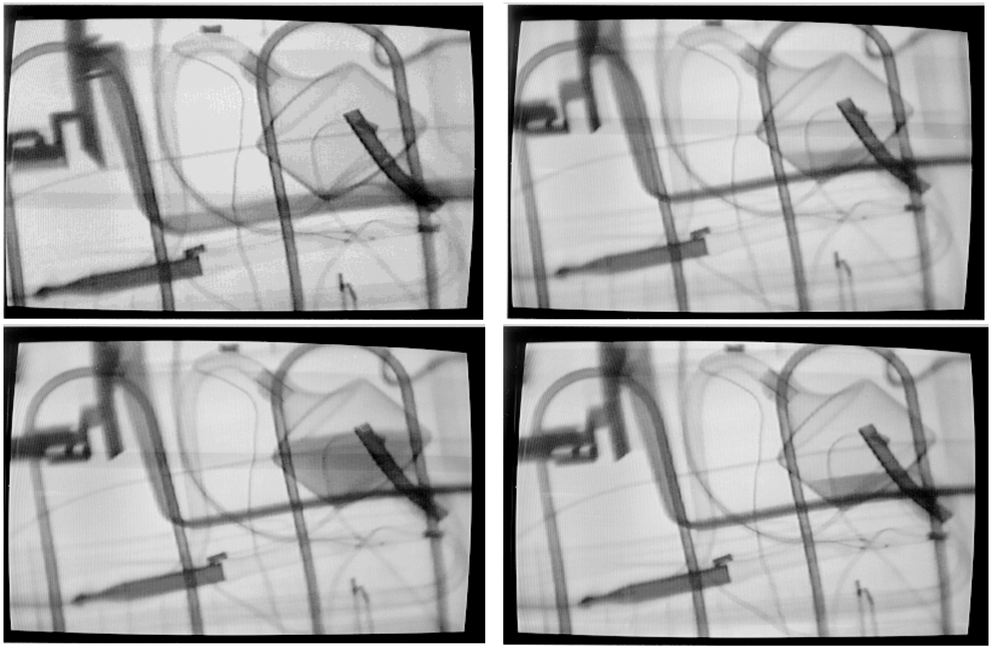

Figure 4: Accumulator photos @24°C. Left to Right , empty accu., First liquid accumulation, max liquid level, liquid drains back after compressor stops.

The maximum refrigerant level in the accumulator is shown in Fig. 5. It is lowest at 12 °C ambient as expected. Because the accumulator inlet tube's outlet limits the maximum level, levels are similar for 24 °C and 43 °C ambient.

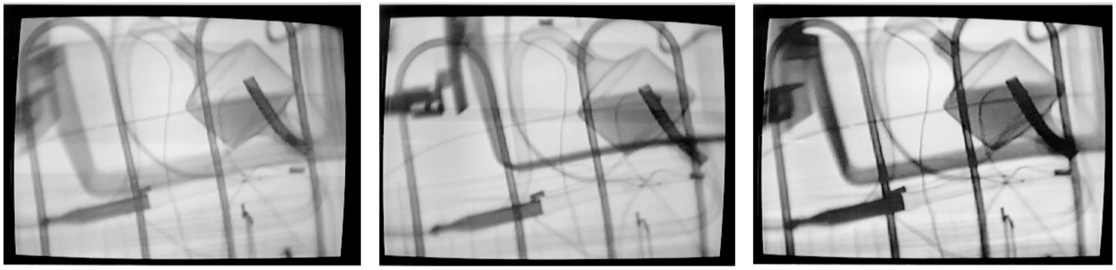

Figure 5: Max liquid level in the accumulator with the ambient temperatures of 12°C,24°C, and 43°C respectively.

Table 2 Some important notices from X-Ray observations (Evaporator and Accumulator section, after the first compressor stop)

Tamb=12 °C	**Tamb= 24 °C (Fig. 6)**	**Tamb=43 °C**
Comp. Stops, liquid in the accu. drains back @1:06:25	Comp. Stops, liquid in the accu. drains back . @1:39:00 **(Fig.6-a).**	Comp. Stops, liquid in the accu. drains back @5:20:00
Very bulk liquid accumulation after the capillary is observed.	Some liquid accumulation after the capillary is observed due to the migration **(Fig 6-a)**	Some liquid accumulation after the capillary is observed due to the migration
Compressor starts again @ 1:22:52. And all liquid pours into accumulator quickly.	Compressor starts again @ 1:51:00 and all liquid pours into accumulator quickly **(Fig 6-b).**	Compressor starts again @ 5:35:15. and all liquid pours into accumulator quickly. The flow after the capillary is visible.

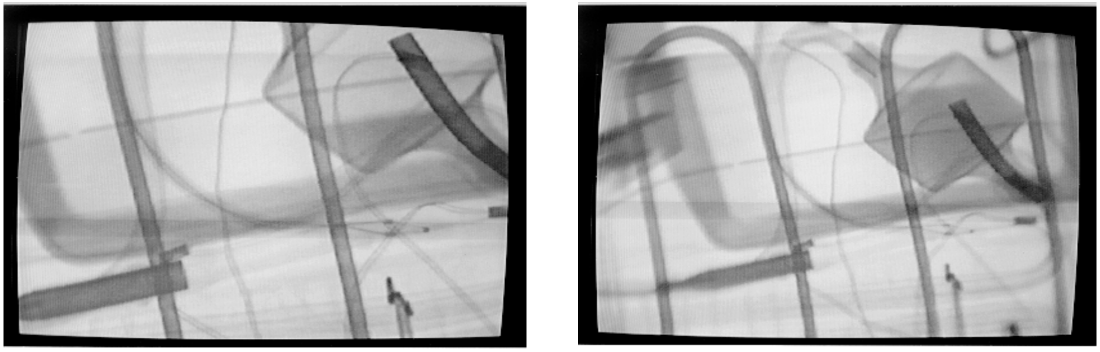

Figure 6: a) Migration during off period, @24 °C b) Quick filling of accumulator just after the re-start of compressor, @24 °C

Table 3 Some important notices from X-Ray observations (Dryer section)

Tamb=12 °C	Tamb= 24 °C	Tamb=43 °C
The first liquid accumulation starts @2nd min, and the dryer fills up completely in 60 s.	The first liquid buildup starts @2.5th min, and the dryer fills up completely in 70 s.	Dryer starts filling up immediately after start-up. Then it is starts decreasing around 13th minute. Finally it is completely empty @ 00:20:00, then it starts filling again @00:22:30. It fills completely in 25s.
The liquid level is above the top of dryer.	The liquid is observed at the top of dryer @ 1:19:45, while subcool decreases. Liquid level is decreasing. **(Fig. 7-b)**	The liquid is observed at the top of dryer @ 1:06:00, while subcool decreases. Liquid level is half @ 1:38:00. It is fluctuating in 15-20 mm 1:42:00. Time to time the liquid level reaches to the bottom @1:46:00, and the dryer is empty @1:58:00
The liquid is emptied in 30s when compressor stops (migration) @ 1:13:10	The liquid is quickly emptied when compressor stops (migration) @ 1:23:37	The subcool of 2.5 K is stable after 3 hours. During that time the liquid in the capillary entrance is not seen. Therefore, it is not clear that there is a real subcoling. Compressor stops @5:20:00
Dryer fills up intermittently. First fills up to half then empty again, this is repeated two times, then fills completely.	After the compressor starts again, the liquid is observed in the dryer in 30 s, and the dryer fills up completely in 60 s.	No observation is made.

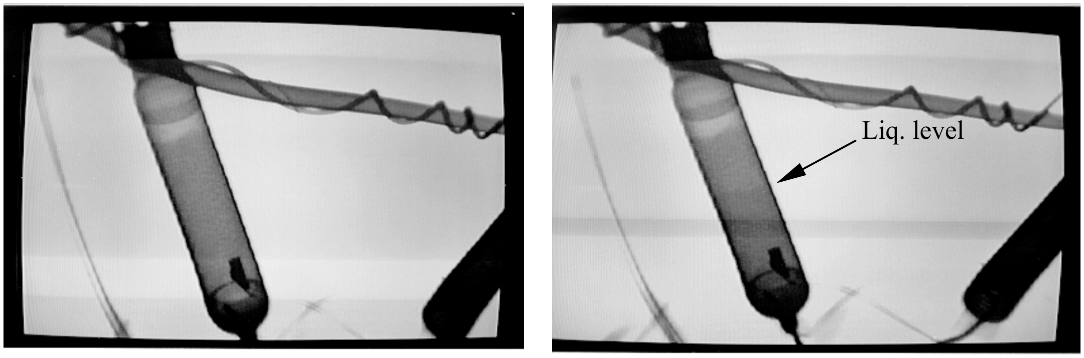

Figure 7: a) An empty dryer before startup b) Liquid level in the dryer is slightly visible

CONCLUSIONS

The following conclusions are made as a results of the study.

- The X-ray system is a very good tool for refrigerant observations. Aluminum tubes are good for better image quality, Steel and even Copper tubes do not give satisfactory results. Therefore use of low-density metals should be considered for better image quality.
- With the help of real time video images, subcooling value at capillary inlet, and temperatures measured form evaporator inlet, and accumulator regions are found quite successful parameters to explain charge distributions and transients in the system. Observations are made only for R-134a. It is not investigated if there is any difference on image quality for other refrigerants.

- At start-up, evaporator inlet temperature decreases sharply and starts to increase some time then decrease continuously for all ambient temperatures. The lowest temperature and the duration to reach to the peak value changes with ambient temperature.
- The subcooling degree at the capillary inlet can successfully be used to explain charge movements.
- The time passed for first liquid arrival to accumulator is important as it can be used for a proof of complete wetness of evaporator. While the ambient temperature decreases the duration of first liquid arrival increases. Since the faster distribution of refrigerant in the cycle decreases the performance losses, some different tube circuiting and also different tube shapes beyond circular ones should be studied.
- When the compressor stops, liquid in the accumulator drains back to the evaporator tubes. During that time the refrigerant migrates from condenser to evaporator. Migrated refrigerant stays in the tubes right after the capillary exit. Depending on the alignment of the evaporator inlet tubes, with the restart of compressor the high velocity refrigerant from capillary hits in to this accumulated liquid. It is possible that some sort of noise may occur; therefore evaporator inlet tube's alignment seems important. Similarly the drained refrigerant pours into accumulator rapidly at restart of compressor. During this time, some of liquid overflows to the suction line and it reach to the compressor at startup. Due to the excessive cooling on the suction line and capillary, it may create unsteadiness on flow characteristics. Moreover, boiling like noises are quite possible, therefore these effects should be considered in accumulator sizing.
- The two-phase refrigerant flow in the tubes is always stratified. Some shock waves are also observed as it is explained by Shedd & Newell [10].

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