Theses and Dissertations

12-2012

Distribution Map of Multi-Walled Carbon Nanotubes in a Refrigerant/Oil Mixture Within a 2.5 Ton Unitary Air-Conditioner

Warren Russell Long
University of Arkansas, Fayetteville

Recommended Citation

Long, Warren Russell, "Distribution Map of Multi-Walled Carbon Nanotubes in a Refrigerant/Oil Mixture Within a 2.5 Ton Unitary Air-Conditioner" (2012). *Theses and Dissertations*. 586.
http://scholarworks.uark.edu/etd/586

DISTRIBUTION MAP OF MULTI-WALLED CARBON NANOTUBES IN A
REFRIGERANT/OIL MIXTURE WITHIN A 2.5 TON UNITARY AIR-CONDITIONER

DISTRIBUTION MAP OF MULTI-WALLED CARBON NANOTUBES IN A
REFRIGERANT/OIL MIXTURE WITHIN A 2.5 TON UNITARY AIR-CONDITIONER

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Mechanical Engineering

By

Warren Long
University of Arkansas
Bachelor of Science in Mechanical Engineering, 2010

December 2012
University of Arkansas

ABSTRACT

In recent years, nanoparticles have received considerable attention as a potential additive to heat transfer fluids (i.e. refrigerant) in order to increase the heat transfer capabilities of these fluids. The potential of carbon nanotubes (CNTs) to exit the compressor, migrate throughout a vapor compression air conditioning system, and possibly foul the components of such a system was experimentally investigated in this research. Six grams of CNTs were dispersed in the polyol ester oil used by a 2.5 ton (8.79 kW) unitary air conditioning system, which was continuously operated for 168 hours. After this time, the unit was shut down and dismantled in order to determine if and where the CNTs had migrated, and to discover any possible fouling. Of the six grams (92.6 grains) initially placed into the compressor, only approximately 2.5 grams (38.6 grains) were recovered from inside the compressor, leaving approximately 3.5 grams (54 grains) distributed throughout the system. A portion of the CNTs found in the system were in the process of flowing with the refrigerant, but the majority had become strongly adhered to the interior walls. The location of the heaviest fouling was found in the first 2-3 feet (0.61-0.91m) of each aluminum condenser circuit. The results indicate that the most conducive environment for CNTs to foul the interior tube walls is when the refrigerant is a superheated vapor. When the refrigerant was at or very close to 0% vapor quality, almost no fouling was observed. This work showed conclusively that CNTs will exit a scroll compressor and have high fouling potential when utilized in a standard vapor compression air conditioning system.

This thesis is approved for recommendation
to the Graduate Council.

Thesis Director:

_____

Dr. Darin Nutter

Thesis Committee:

_____

Dr. Steve Tung

_____

Dr. Larry Roe

THESIS DUPLICATION RELEASE

I hereby authorize the University of Arkansas Libraries to duplicate this thesis when needed for research and/or scholarship.

Agreed _____
          Warren Long

Refused _____
          Warren Long

ACKNOWLEDGEMENTS

DEDICATION

To my parents: Leslie and Cyrill Long

TABLE OF CONTENTS

INTRODUCTION

There are several reasons that validate the need for extensive research into energy conservation. First, the world's population is growing larger, meaning demand for energy is growing as well; and, the supply of coal, our primary means of electrical power generation (EIA 2012), is finite. Furthermore, the burning of fossil fuels for energy production may negatively impact our planet in areas such as global warming (EPA 2012).

As with the rest of the world, the United States' population is growing. The more populated regions of the United States already experience occasional, intentional 'brownouts' as electric companies, in an effort to avoid complete blackouts, lessen the voltage supplied to their customers for a period of time. These brownouts are due to the very high demand placed upon the electrical supply grid. Demand can only continue to grow unless many conservation methods are aggressively pursued and implemented. If these changes are not made, the occasional, and unacceptable brownouts will likely transition into increased occurrences of complete blackouts.

Another important reason to pursue means of energy conservation is national security. Any country, such as the United States, that imports energy sources from another country is at the mercy of that exporting country (or group of countries). As the United States has experienced, this presents a very real national security problem to a country that relies on foreign sources of energy. Although advances in air conditioning system efficiencies will not resolve this problem alone, the overall pursuit of increased energy efficiency will certainly lessen foreign energy dependence. Though our primary energy dependence is petroleum, it is the general conservation of natural resources that will extend the availability of these resources to future generations. It is for these reasons that potential energy saving techniques should be investigated.

Nanoparticles have received significant attention from the scientific community in the past 10-20 years. Nanoparticles are less than 100nm in diameter (Choi 2009); this diameter can apply to a spherical nanoparticle, or the diameter of a tube, such as a carbon nanotube (CNT). Nanoparticles have several various uses that span different fields, such as medical and materials engineering. 'Nanorefrigerant' is the term coined to describe refrigerant containing nanoparticles dispersed within (Choi 1995). These nanorefrigerants have shown good potential to increase heat transfer in heat exchangers, such as an evaporator. This paper addresses the possibility of implementing nanorefrigerants in a vapor compression air conditioning system.

Although most nanoparticles will increase the host fluids' overall thermal conductivity and the majority of research into heat transfer coefficient improvement has been positive, there are a few practical questions in need of answering and/or obstacles to be overcome. One of these concerns is the potential for these nanoparticles to adhere to and collect on the heat transfer surfaces. Depending upon the extent of this fouling, it could severely impair the heat transfer ability of the heat exchangers. Another question in need of investigation concerns the migration potential of nanoparticles when in use by an actual air conditioning system. If the nanoparticles are to be inserted in the compressor, will they ever migrate to a position where they can be of use? It is these two possible difficulties that were explored in this study.

A packaged air conditioning system with R-410a was used for the refrigeration system along with carbon nanotubes since those nanoparticles have produced very positive results in heat transfer research. The nanotubes were dispersed in polyolester oil, ultra-sonified, and then added to the system's compressor. The system was then recharged with R-410a and continuously run for seven days. Then the system was evacuated of refrigerant and was dismantled to find evidence of migration from the compressor and any deposition of the CNTs within the unit.

Methanol was used to flush any loose CNTs from the inside of all tubing. All tubing was cut open, inspected and photographed in order to put together a 'map' of nanoparticles that clung tightly throughout the system. The nanoparticles flushed from the system, including those from the compressor, were weighed to give an indication of the quantity of CNTs that were flowing through the system, were stuck in the tubing of the system, or were still in the compressor

Determining the distribution of nanoparticles in a refrigeration system after a significant runtime was very important. Some research on friction characteristics and oil/refrigerant miscibility has shown evidence that nanoparticles may increase the efficiency of the compressor (Wang and Xie 2003). Therefore, nanoparticles may have a dual impact on efficiency, but it needed to be known how the nanoparticles distribute themselves after runtime, and where they are inserted initially may be of utmost importance.

Again, the purpose of this thesis is to experimentally determine the distribution of nanoparticles after a runtime of one week. The next chapter of this thesis is a complete paper: 'Distribution Map of Multi-Walled Carbon Nanotubes in a Refrigerant/Oil Mixture within a 2.5 Ton Unitary Air-Conditioner'; this paper is to be submitted to *ASHRAE Transactions*. The initial sections of chapter 2 will provide an introduction and a background description of the areas of nanofluid research. Secondly will be a review of the experimental methodology, followed by the results and a topical discussion of these results. Lastly, conclusions obtained from this work will be presented followed by the future work necessities that were highlighted by this study. Chapter 3 is an overview of the definitive conclusions obtained from this study.

REFERENCES

Choi, S. 1995. Enhancing thermal conductivity of fluids with nanoparticles. *Developments and Applications of Non-Newtonian Flows* MD-66:99-103.

Choi, S. 2009. Nanofluids: From vision to reality through research. *Journal of Heat Transfer, Transactions of the ASME* 131:1-9.

eia.gov. U.S. Energy Information Administration. May 2, 2012. Web. Accessed: August 23, 2012.

epa.gov. Environmental Protection Agency. June 14, 2012. Web. Accessed: August 23, 2012.

Wang, R., and Xie, H. 2003. A refrigerating system using HFC134a and mineral lubricant appended with N-TiO$_2$(R) as working fluids. *Proceedings of the 4th international symposium on HVAC, Tsinghua University.*

DISTRIBUTION MAP OF MULTI-WALLED CARBON NANOTUBES IN A REFRIGERANT/OIL MIXTURE WITHIN A 2.5 TON UNITARY AIR-CONDITIONER

ABSTRACT

In recent years, nanoparticles have received considerable attention as a potential additive to heat transfer fluids (i.e. refrigerant) in order to increase the heat transfer capabilities of these fluids. The potential of carbon nanotubes (CNTs) to exit the compressor, migrate throughout a vapor compression air conditioning system, and possibly foul the components of a such a system was experimentally investigated in this research. Six grams of CNTs were dispersed in the polyol ester oil used by a 2.5 ton (8.79 kW) unitary air conditioning system, which was continuously operated for 168 hours. After this time, the unit was shut down and dismantled in order to determine if and where the CNTs had migrated, and to discover any possible fouling. Of the six grams (92.6 grains) initially placed into the compressor, only approximately 2.5 grams (38.6 grains) were recovered from inside the compressor, leaving approximately 3.5 grams (54 grains) distributed throughout the system. A portion of the CNTs found in the system were in the process of flowing with the refrigerant, but the majority had become strongly adhered to the interior walls. The location of the heaviest fouling was found in the first 2-3 feet (0.61-0.91m) of each aluminum condenser circuit. The results indicate that the most conducive environment for CNTs to foul the interior tube walls is when the refrigerant is a superheated vapor. When the refrigerant was at or very close to 0% vapor quality, almost no fouling was observed. This work showed conclusively that CNTs will exit a scroll compressor and have high fouling potential when utilized in a standard vapor compression air conditioning system.

5

INTRODUCTION

Due to the increasing cost and increasing demands on a finite supply of fossil-fuel based energy, many households, businesses, and commercial suppliers are turning toward innovative ways to conserve. One opportunity for improvement is to increase the efficiency of vapor compression air-conditioning systems (i.e., unitary air-conditioners and heat pumps) via enhanced heat transfer within the condenser and evaporator. Passive techniques are of particular interest since they do not require any additional system power. Examples of these successful 'passive enhancement' measures, which are currently employed, include axial ribs or helical fins. According to Park and Jung (2007) these passive techniques have reached their limitations for improvement to heat transfer. However, in recent years, enthusiasm for nanoparticles and their use for passive enhancement, in ever increasing applications, has been gaining momentum. Although the use of nanoparticles has been around for several hundred years (Choi 2009), the reliable production of high purity nanoparticles has only recently been achieved. Since then, the term 'nanoparticle', has become a common scientific term.

More specific to unitary air-conditioners and heat pump improvements, nanorefrigerants are being investigated. They are composite fluids made up of a heat transfer liquid, such as water or refrigerant; usually a small volume percentage of nanoparticles, varying in shape and material; and possibly small amounts of refrigerant oil and/or stabilizers. The aim of nanorefrigerant applications is to increase heat transfer effectiveness between the heat transfer area, in an evaporator tube for instance, to the heat transfer fluid.

Although it has long been known that adding highly conductive particles to a fluid will increase the heat transfer into and through the fluid, larger "micro-particles" in the fluid require more pumping power and systems can become clogged. Nanoparticles in these new nanofluids

are less than 100 nm in size. Nanorefrigerants seem to be most promising at low mass or volume fractions: less than 1.0%. This avoids the problems commonly associated with larger particles. Research on nanofluids began in 1995 with the aim of increasing the fluids' thermal conductivity (Choi 1995). Fluids by themselves have relatively poor thermal conductivity. Water only has a thermal conductivity of about 0.6 W/m-K (0.35 Btu/hr-ft-F), and is the highest of the heat transfer fluids (Ding et al. 2009). Along with possible heat transfer improvements, research on friction characteristics and oil/refrigerant miscibility have shown evidence that nanoparticles may increase the efficiency of the refrigerant compressor (Wang and Xie 2003).

Nanorefrigerants have had some promising results in recent heat transfer research (Kedzierski 2009; Liu and Yang 2007; Park and Jung 2007a and 2007b), but there are many potential obstacles to overcome before the energy savings of these refrigerants can be realized. One of these obstacles is the potential for these nanoparticles to become dispersed and foul the system's components where they are of no assistance to heat transfer, and possibly a hindrance, especially if they foul heat exchange surfaces. More specifically, the only studies on the efficiency improvements of adding nanoparticles to a vapor compression refrigeration system have been with a household refrigerator; however, the researchers did not study the distribution of the nanoparticles throughout the system (Bi et al. 2011; Bi et al. 2008; Jwo et al. 2009).

The research presented in this thesis is an investigation of migration and fouling tendencies of multi-walled carbon nanotubes (MWCNTs) in a 2.5 ton (8.79 kW) unitary air-conditioning system.

BACKGROUND/REVIEW

Thermal Conductivity

A large portion of the research into nanofluids has investigated their combined, or effective, thermal conductivity. As mentioned previously, fluids have a relatively poor thermal conductivity. Carbon nanotubes (CNTs) are a promising nanoparticle for use in nanofluids; and, they can have thermal conductivities on the order of several thousands of W/m-K (Berber et al. 2000). Research is required in this area because there are so many factors, including: base fluid; additives, such as oil; nanoparticle material; nanoparticle size; nanoparticle shape; and nanoparticle concentration. In 2009 it was shown that CNTs increased the thermal conductivity of R-113 more effectively than spherical nanoparticles constructed of metal or metal oxides. The materials used as a comparison to CNTs were copper, aluminum, nickel, copper oxide, and aluminum oxide. In addition, the smaller the diameter of the CNTs, the more the thermal conductivity was increased (Jiang et al. 2009). Attesting to the sensitivity of concentration, Eastman et al. (2001) showed that the thermal conductivity of ethylene glycol can be raised by 40% with just a 0.3% addition of copper nanoparticles. The importance of knowing how the thermal conductivity of the fluid is affected by the addition of a particular nanoparticle is so that the optimal concentration of nanoparticles may be employed within the host fluid (Jiang et al. 2009). Although thermal conductivity is important, there are other factors influencing the possible increase in heat transfer.

Boiling Heat Transfer

The majority of the research in nanofluids for heat transfer applications has been around boiling heat transfer. Because the evaporator in a refrigeration system consists of convective, boiling heat transfer, this focus is well founded. Within the literature, there are many conflicting conclusions to these studies: some experiments result in a demonstrated increase in the heat transfer coefficient (HTC), some show a decrease, and some have mixed conclusions. As

examples, only a fraction of this type of research is discussed below (Table 1 displays the comprehensive results of these works). Kedzierski (2009) found that, using CuO nanoparticles in R-134a and at a 0.5% volume concentration, there was heat transfer degradation; but, at a 1% volume concentration, the HTC improved. Liu and Yang (2007) saw more than a 100% increase in the pool boiling HTC for R-141b using gold nanoparticles at a 1% volume concentration. However, it was found that the nanoparticles deposited onto the heat transfer surface, which resulted in progressively smaller and smaller improvement (in HTC) for subsequent tests. Even after cleaning the surface, they were never able to achieve the initial level of increased HTC. This deposition, or fouling, was not seen by Park and Jung (2007a and 2007b) using carbon nanotubes with refrigerants R-22, R-123, and R-134a. Each of these experiments resulted in HTC improvements. The improvements were most significant at heat fluxes of about 20-30 kW/m^2 (6340-9510 Btu/hr-ft^2); as heat flux increased the improvements were less pronounced. The researchers theorized that with more bubble generation (i.e., at higher heat fluxes) the nanoparticles were not as likely to come into contact with the heat transfer surface, an important interaction for the formation of vapor bubbles. In 2009, Trisaksri and Wongwises published their research that indicated reduced HTC performance using R-141b with TiO_2 nanoparticles. The researchers theorized that the HTC degradation was due, in part, to the use of low nanoparticle concentrations (maximum of 0.05% by volume). This theory may have merit, as the successful pool boiling experiments tend to be in the range of 0.1-1.0%, by volume concentration. Similarly, Das et al. (2003) used Al_2O_3 nanoparticles in water with concentrations ranging from 0.1%- 4%, by volume. The researchers theorized that, since the nanoparticles were smaller than the surface roughness, they became trapped on the surface (thereby changing the surface characteristics), resulting in diminished HTCs.

Convective Heat Transfer

Another area of research has been in single phase convective heat transfer. Ding et al. (2006) conducted an experiment with CNTs suspended in an aqueous solution flowing through a horizontal tube, which was the heat transfer area. The researchers found an improvement in heat transfer over pure water. They also found that the enhancement depended upon the Reynolds number and the CNT concentration. At a concentration of 0.5% by *weight* and Re=800, the HTC improvement reached 350%. The researchers said that enhanced thermal conductivity couldn't have been the only reason; it was theorized that the large improvement was also due to "particle re-arrangement, shear induced thermal conduction enhancement, reduction of the thermal boundary layer due to the presence of nanoparticles as well as the very high aspect ratio of CNTs". The disruption and reduction in the thermal boundary has been mentioned by others as well (Wen and Ding 2004; Peng et al. 2009). Though thermal conductivity receives the most attention, several authors acknowledge the Reynolds number, which includes density and viscosity, as an important factor. The presence of nanoparticles alters the fluid's properties. Specific heat capacity, density, and thermal conductivity increases can increase the HTC; and decreases in viscosity can increase the HTC. While nanoparticles increase the thermal conductivity, they usually lower the specific heat capacity, as liquids generally have a higher heat capacity; and they increase the effective viscosity (Wen et al. 2009). These factors are conflicting, in terms of HTC improvement, and could be a reason for the disagreements between the various researchers' findings.

Turbulence intensification is another possible factor mentioned by researchers to at least partly explain potential convective HTC improvements. However, this theory, like many others in this specific field, has not been universally agreed upon. In 2006, Buongiorno proposed that

10

HTC improvement by turbulence intensification is "doubtful". Later, in 2010, Godson et al.

concluded that "suspended nanoparticles…increases fluctuation and turbulence of the fluids

which accelerates the energy exchange process".

Table 1. Previous Nanorefrigerant Heat Transfer Results					
Nanoparticle	**Fluid**	**Percentage**	**Result**	**Author**	**Year**
CuO	R-134a	0.5% vol	Degradation	Kedzierski	2009
CuO	R-134a	1.0% vol	Improvement	Kedzierski	2009
Gold	R-141b	1.0% vol	Improvement: 100%	Liu and Yang	2007
CNTs	R-22 R-123 R-134a	1.0% vol	Improvement: 28.7 % 28.6% 36.6%	Park and Jung	2007
TiO_2	R-141b	0.05% vol	Degradation	Trisaksri and Wongwises	2009
Al_2O_3	Water	0.1-4% vol	Degradation	Das et al.	2003
CNTs	Water	0.5% mass	Improvement: 350%	Ding et al.	2006

**Table 1. Improvements and degradations to heat transfer utilizing different types of
nanoparticles. Though some research has found nanoparticles detrimental to heat
transfer, there has been enough encouraging results to validate continuing research.**

Preparation

An important aspect in nanofluids is the preparation. Many studies have used R-113 because

it is liquid at standard temperature and pressure (STP); hence the refrigerant will not boil away

while preparing the nanofluid. Preparing a nanorefrigerant that isn't liquid at STP presents

another level of difficulty. Another problem is that nanoparticles can become agglomerated by

Van der Waals forces. When this happens, it negatively affects the enhancement possibilities

that nanofluids may provide. Dry nanoparticles received in "powder" form are mostly

agglomerations; these are broken up, once in the fluid, by various methods including magnetic

stirrers and ultrasonic baths (the most popular method). In order to perform significant research

using nanofluids, the agglomerations of nanoparticles must be broken up; else the nanoparticles form micro (or milli) - particles. Once dispersed in the fluid they can be held apart by electrostatic repulsion and "steric repulsion". Stabilizers such as laureate salt are also used to keep the nanoparticles separated. It is worth noting that, in some experiments, the stabilizer may not be noted and the nanofluid with the stabilizer is compared to the pure fluid, meaning the addition of the nanoparticles are only one of two possible factors (Wen et al. 2009). Sedimentary stability refers to how well the nanoparticles remain suspended in the nanofluid, overcoming the tendency to fall to the bottom. Wu et al. (2009) say that there are three factors to consider when trying to achieve sedimentary stability. They are viscosity of the base fluid; density difference between nanoparticles and the base fluid; and the size of the nanoparticles. Another important aspect in sedimentary stability is agglomeration. If the nanoparticles agglomerate, their size effectively becomes larger; this can decrease their sedimentary stability (Choi 2009; Jiang et al. 2010).

Migration

Overall, there is very little research into what happens to the nanoparticle during fluid phase change; however, this idea has been explored more often in recent years. In 2009, Ding et al. investigated the amount of nanoparticles that stayed behind in a cup after complete boiling. They used copper-oxide (CuO) nanoparticles and refrigerant R-113. The researchers found that, although most nanoparticles remained in the cup, some do exit with the vaporized refrigerant. The range of nanoparticles that migrated away was between 1.15% and 5.8%, by *mass*; the lower part of the range occurred when compressor oil was mixed with the refrigerant and nanoparticles. The researchers had two theories for the manner in which the nanoparticles escaped: "individual escaping way" and "bubble adhesion way". The individual escaping way is based upon the fact

that all the nanoparticles have their own Brownian motion but only the nanoparticles with high velocity can break the surface tension and escape. The bubble adhesion way is described as the nanoparticles adhering to the vapor bubbles, rising to the surface with the bubbles, and being blown out at the surface by the high speed gas as the bubbles would burst. The researchers found that the more refrigerant there was to boil out initially, the higher the percentage was of escaped nanoparticles.

Another, more recent study on the migration characteristics of nanoparticles was conducted by Peng et al. in 2011. This study used a variety of conditions, but all focused on CNTs migrating from boiling refrigerant; some with dissolved oil as well. The researchers found a migration ratio as high as 27.8%, by volume; the other tests were within 1.5% and 8%. The highest migration, 27.8%, was achieved using a relatively large CNT diameter of 80nm and length of 10 microns. These were the largest CNTs used, and suggested that at least up to a point, the larger sizes of nanoparticles resulted in a higher migration ratio.

Although these former studies have shown migration occurs, these experiments do not exactly replicate the conditions in an air-conditioner's evaporator. These tests were for pool boiling: the refrigerant is boiled completely off, using a specific heat flux, and then repeatedly weighed until all refrigerant has been evaporated. In contrast, an evaporator is more complex and has a continuous supply of two-phase refrigerant, and if nanoparticles do travel throughout the system, a continuous supply of nanoparticles as well. This may create the potential for nanoparticle accumulation. Experimental knowledge of the migration characteristics of nanoparticles in an evaporator is needed and currently unavailable. Further studies are needed.

Application

Because nanorefrigerant research is still a relatively new area, very few actual applied experiments have been conducted. Most have been basic pool boiling or convection experiments that attempt to find an improvement of the HTC. However, recent experiments with the performances of household refrigerators charged with nanorefrigerant versus pure refrigerant were a beginning next step. These experiments are discussed below.

Bi et al. (2008) published their experiment that analyzed the performance of a refrigerator using nanorefrigerants. The researchers used TiO_2 (they also tested Al_2O_3), R-134a and mineral oil (instead of the more common polyol ester (POE) oil). The choice of oil is a significant substitution. According to these researchers, POE oil can lead to severe friction in the compressor since POE oil is hydroscopic and hydrolytic. POE oil is used due to its miscibility with the HFC refrigerant, but Wang and Xie (2003) found that nanoparticles may increase the solubility between mineral oil and HFC refrigerant. Bi et al. (2008) found energy consumption savings ranging from 20.86% to 26.13%. The study also included tests that used just mineral oil and refrigerant (i.e., without nanoparticles). These tests yielded a 16.67% reduction in energy use; less than where nanoparticles were present.

In 2011, Bi et al. compared a nanorefrigerant of TiO_2/R600a to pure R600a in a domestic refrigerator. The researchers found a 5.94% energy consumption savings, using 0.1 g/L (5.8 grains/gal); and, at 0.5 g/L (29 grains/gal) they achieved a 9.6% savings. Also, compared to pure R600a, the time it took the freezer compartment to reach freezing temperature was reduced. The researchers theorize two possible mechanisms for the increase in energy savings when nanoparticles were present in the refrigerant relative to the mineral oil only tests. One idea was that the nanoparticles further reduced the compressor friction. The other possibility was that

nanoparticles in the evaporator improved the heat transfer. The authors concluded that the distribution of nanoparticles and these mechanisms need to be investigated. If the benefits of nanoparticles for heat transfer are to be taken advantage of, the distribution of the nanoparticles throughout the refrigeration system, after some time in use, is of primary importance. The authors did not know if the nanoparticles even made their way into the evaporator section, or if they somehow become lodged and immobile elsewhere. There may be measures that can be devised to ensure their usefulness in the heat exchangers.

METHODOLOGY

The objective of this research was to map the migration and fouling tendencies of multi-walled carbon nanotubes (MWCNTs) in a 2.5 ton (8.79 kW) unitary air-conditioning system. The MWCNTs used in this research were purchased from Nano-Lab. The CNTs were 15 ± 5 nm in diameter and 5-20 microns in length; and were >95% purity (as expressed by the manufacturer). Two preliminary tests were performed and the results used to design the primary packaged air-conditioner experiment. Methodologies for both are discussed below.

Preliminary Test

Because the primary experiment would require the refrigerant to be evacuated, two preliminary tests were run using a simple apparatus (Fig 1). The device utilized copper tubing, quick release connections, a pressure gauge, a pressure relief valve, and an exit valve. These tests were used to determine if the nanoparticles would remain in place while the primary test apparatus (2.5 ton (8.79 kW) unitary air-conditioning system) was evacuated at the end of its operation. R-113, MWCNTs, and a small amount of POE oil were inserted into the arrangement. The valve was closed and the device was heated by a hot water bath to about 180 F (82.2 C),

well above the boiling temperature of R-113, 117.7 F (47.5 C). Although it was assumed that a rapid release of the refrigerant from the device would greatly disturb the position of the CNTs, and they would likely exit through the valve, the assumption needed to be verified. The device was held in the hot water bath until the pressure stabilized; then the valve was quickly and fully opened. The very small amount of remaining CNTs were weighed, and, as hypothesized, most CNTs had been expelled from the arrangement.

Figure 1. Device designed to test the tendencies of CNTs during evacuation of refrigerant.

The purpose of the second test was to determine if the CNTs could remain undisturbed from their position during slow evacuation of the refrigerant. The same methodology was used as before, except after the addition of the refrigerant, CNTs, and oil, a swath of white cotton cloth was placed over the exit tube. The device was heated again. This time the valve was opened just enough to audibly verify that refrigerant was escaping. After all refrigerant was expelled, the device was inspected. Quick release connections were used in the assembly in order to facilitate ease of inspection. The cloth showed no visible evidence that any nanoparticles were carried to the exit valve by the refrigerant, as the white cloth was unblemished by CNTs. Also, the stem

leading up to the valve, and the valve itself, had no sign of any CNTs on their walls. The CNTs and POE oil were left in a continuous channel at the gravity bottom of the tubes. This verified that refrigerant can be evacuated while leaving the nanoparticles relatively undisturbed. Also, it was found that a methanol flush of the tubes worked very well in removing the oil and CNTs.

Packaged Air-conditioner Test

A 2.5 ton (8.79 kW) packaged air-conditioning unit was used to 'map' the distribution of CNTs throughout a refrigeration system after a run-time of 168 hours of continuous operation. The packaged air-conditioner utilized a scroll compressor, enhanced copper tube evaporator, enhanced aluminum tube condenser, and a thermal expansion valve (TXV). After the test, the entire unit was destructively disassembled and analyzed.

The run-time of 168 hours was chosen based the goal to allow the compressor lubricant (POE oil) to travel 1,000 cycles through the system. For this air-conditioning system, it was estimated that the refrigerant would make on the order of 11,000 cycles over a period of 168 hours. It is possible for a vapor compression air-conditioning system to have as much as 8-16% of their total oil flowing with the refrigerant (Johnson Controls 2009; Bi et al. 2008); therefore the oil could conceivably circulate through the system 1,000 times over the course of 168 hours.

The following checks and modifications were made to the 2.5 ton (8.79 kW) unitary air-conditioning system. First, the system was run, as delivered, to ensure functionality. After verifying that the system was operating properly, the unit was shut off to begin physical modifications. The refrigerant, R410a, was evacuated and recovered. Next, the compressor was detached from the system and the majority of POE oil removed and stored (675 mL or 2.85 cups). The oil was protected from the environment to avoid contamination by water.

Upon compressor shutdown, refrigerant within a normally operating system will migrate throughout the unit based on temperature and pressure differences. Therefore, this system required a mechanism for isolation of the components to ensure refrigerant and CNTs remained in place upon shutdown, and did not migrate to other parts of the system. In order to accomplish this, three quarter-turn ball valves were installed: one between the compressor and condenser; one between the condenser and TXV/evaporator; and another between the evaporator and condenser. This allowed for quick isolation of the components upon compressor shutdown. The quarter-turn valves also had access ports (i.e., valve stem assemblies) in order to remove the refrigerant from the three isolated sections. In addition, the liquid-line filter-dryer was removed from the system.

Prior to the insertion of the CNTs, ultrasonification within the POE oil was used to eliminate agglomeration. Of the 675 mL (2.85 cups) of oil removed from the compressor, 500 mL (2.11 cups) were used as the host to the CNTs for ultrasonification. Six grams (92.6 grains) of CNTs were ultrasonified within the POE oil medium for 20 minutes. Within 45 minutes of its removal, the oil/CNT mixture was reinserted into the compressor by way of funnel and tube (Fig 2). The 175 mL (0.74 cups), and an additional 200 mL (0.85 cups) of oil were used to flush residual CNTs into the compressor. This system normally utilizes 4.2 cups (994 mL) of oil; the addition of 200 mL (0.85 cups) creates a total of 5.05 cups (1194 mL) of POE oil in the compressor. This is an excess oil percentage of about 19%. POE oil has a density of 0.98 g/mL (8.18 oz/cup); therefore the total mass of oil used in this experiment was 1170 g (41.3 oz). Six grams of CNTs were used in this experiment; the mass percentage of CNTs/oil was found to be 0.51%. No surfactants or stabilizers were used.

Figure 2. Pouring CNT/oil mixture into the scroll compressor by way of funnel and tube.

Next, the system was recharged with its original 6.3 lbs (2.86 kg) of refrigerant and checked for leaks. An electronic refrigerant leak detector was used, as well as a visual leak detection spray solution. No leaks were detected and the system was energized. The elapsed time from ultrasonification to system restart was about 1.5 hours.

The system was then energized and run without being shut off for seven days. During this time the unit was monitored to ensure functionality and steady operation. Upon system shutdown, the three quarter-turn ball valves were closed as quickly as possible, isolating the different components, within 10 seconds. The unit was then evacuated of refrigerant. Using the knowledge garnered previously concerning the evacuation rate of refrigerant with respect to CNT migration, the R-410a was very slowly removed. After about 1.5 hours, all refrigerant was removed from the unit.

In order to map CNTs within the system, it was dismantled piece by piece, beginning with the high pressure tube leaving the compressor. All components of the system (including the compressor) were cut apart and opened; flushed for loose CNTs; and photographed in order to map the distribution of the CNTs found throughout the system. All flushed CNTs were weighed,

19

and the remaining adhered CNTs were accounted for using an approximate mass balance method. Because the flushed CNTs contained POE oil, R-113 was used to separate the oil during the filtering process due to the fact the R-113 is miscible with the POE oil.

RESULTS

Figure 3 is a simplified sketch of the packaged unitary air-conditioner used. Shading throughout the diagram was used to show the relative amount of CNTs throughout the system immediately after shutdown and the refrigerant removal (i.e. evacuation) step. A relative scale of '0-10' was used. These 'scores' were awarded on a relative, linear basis. Even with different types of tools it wasn't possible to remove all CNTs from the walls, especially in the condenser tubing. Enough could be removed, however, to obtain an estimate for a rating of '10'. This score corresponds to approximately 0.1 grams of CNTs discovered per foot of tube (0.33 g/m or 1.54 grains/ft) designated as such. While the condenser fouling displayed very strong adhesion, some portions, such as the section between the evaporator and compressor, showed weaker adhesion and were able to be removed by a single methanol flush. Figure 4 shows the schematic of the system *after* flushing, and indicates the sections where CNTs were more strongly adhered. Table 2 shows the mass balance of both CNTs flushed from various system components and approximated values for strongly adhered CNTs that were not able to be removed by flushing. Following is an explanation of the results.
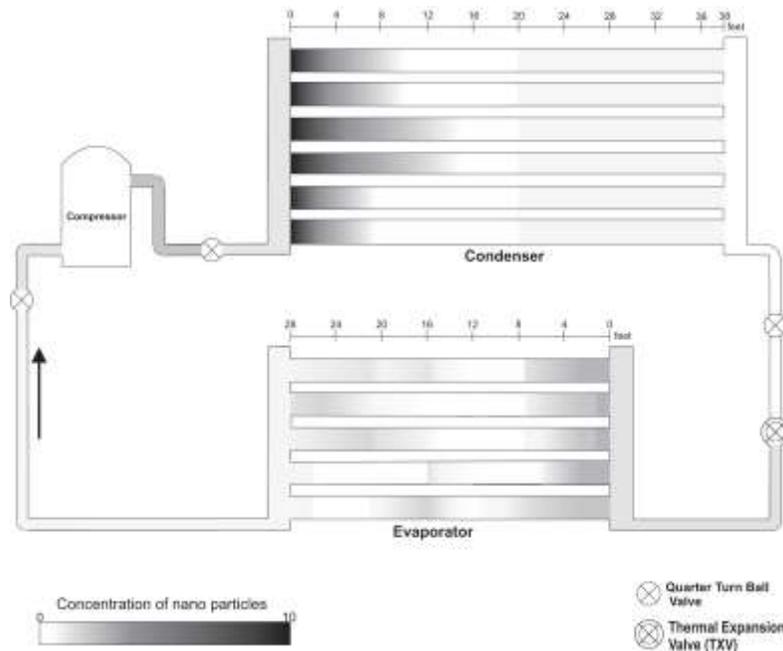
Figure 3. Schematic showing the presence of CNTs (of varying degrees of adhesion) found throughout the vapor compression unit. Though a significant amount of CNTs were recovered from the compressor, this section of the schematic is not shaded due to the fact that the compressor has a much different layout than the rest of the system and does not conform to the basis of the CNT density approximation. See Table 2 for the quantities of CNTs recovered through system/component flushes.
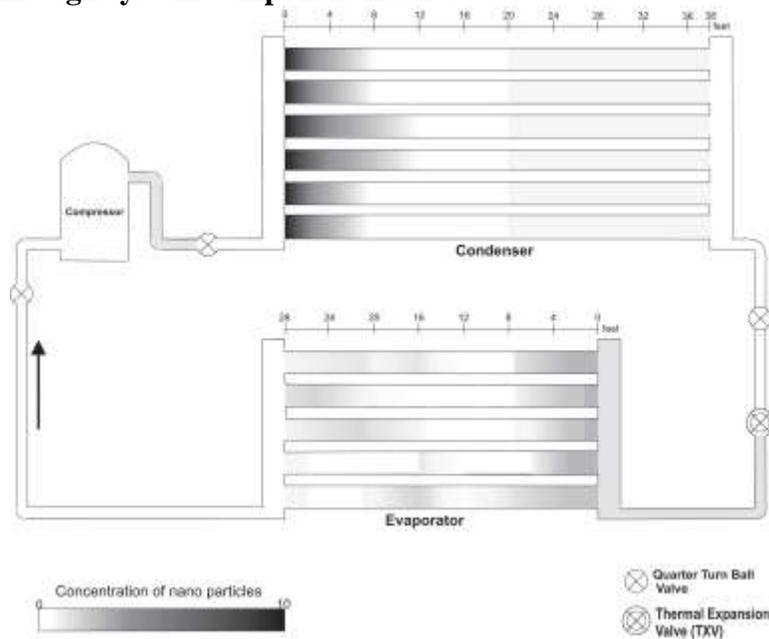

Figure 4. Schematic showing the presence of strongly adhered CNTs found throughout the vapor compression unit. The shading in this diagram indicates the relative density of CNTs *after* flushing. Note the differences between Fig 3 and Fig 4; especially notable is in the discharge and suction lines.

Table 2. Mass Balance of CNTs throughout the System			
Component	**Flushed CNTs (grams)**	**Estimated Fixed CNTs (grams)**	**Total (grams)**
Compressor: Dome (High Pressure)	0.59	<0.02	~0.60
Scroll and Oil Sump (Low Pressure)	1.88	<0.05	~1.93
Discharge Line: Compressor - 1st Isolating Valve	0.15	0.10	0.25
1st Isolating Valve - Pre-Condenser Manifold	0.05	<0.01	~0.06
Condensing Circuits: #1 (Top)	0.10	0.30	0.40
#2	0.15	0.25	0.40
#3	0.20	0.30	0.50
#4	0.10	0.40	0.50
#5	Negligible	0.20	0.20
#6 (Bottom)	Negligible	0.20	0.20
Liquid Line: Post-Condenser Manifold - TXV	<0.001	<0.001	<0.001
Evaporator: Five Evaporator Circuits (Combined)	*0.25 Est.	0.50	0.75
Suction Line: Evaporator - Compressor	0.20	<0.01	0.20
TOTALS	~3.67	~2.30	~5.97

Table 1. This table shows the mass balance results of CNTs that were flushed, and the estimated amounts that were strongly adhered and could not be removed via flushing (see Fig 4). The totals are also shown. Of the six grams introduced to the system, approximately 5.97 grams were accounted for by recovery and approximation. The scale's uncertainty was ±0.05 g (*excluding the evaporator circuits, which were estimated).

Although it was initially hypothesized that a very small fraction of the CNTs would be traveling throughout the system, it soon became clear that the majority of CNTs were outside the compressor at any given time. As soon as the fitting was detached from the high pressure side of the compressor, CNTs could be seen in two flattened 'pea-sized' clusters located about a half-inch (~12.5 mm) into the tube. The copper pipe leading from the compressor to the condenser manifold is about three feet (~1 m) long with an inside diameter of 15/32 inch (11.9 mm); the pipe also had the first of three isolating quarter-turn ball valves. As shown in Fig 3, the concentration of CNTs in this section diminished, but was never completely free of CNTs. The area density of the CNTs in the segment between the compressor and first isolating valve was approximately 3.2×10^{-6} grams per square millimeter (0.032 gr/in^2). Another point of interest in this part of the system is that, at points where valve stems extend into the cross section of the pipe, there was a small buildup of CNTs.

The 3/16 inch (4.76 mm) inside diameter copper tubes from the pre-condenser manifold transitioned to 3/16 inch (4.76 mm) aluminum tubes with interior axial ribs. One of the most unexpected results of this project was the dramatic immediate increase in adhered CNTs once the aluminum condenser section began. The nanoparticles completely coated the entire circumference of the tube to the point that it was very difficult to discern the peaks from the valleys of the ribbed inside. The beginning of each of the six condenser circuits were very similar, and were all rated as a '10' in Fig 3. As noted previously, this rating is estimated at 0.1 g/ft (0.33 g/m or 1.54 grains/ft) of condenser line. The fouling eventually diminished to just a 'stripe'. Where the area fouling did occur in the condenser, it was found to have an area density of approximately 1.6×10^{-5} grams per square millimeter (0.16 gr/in^2). In all six circuits the concentration of CNTs decline to zero at a maximum of 15 feet (4.6 m). Figure 5 shows

representative images from condenser circuit one at four different points within the first 10 feet (3.05 m); each image length is about one inch (25 mm). As can be seen, the fouling began as total circumference coverage but became increasingly localized ending in a thin 'stripe', but not at the gravity bottom of the tube. It seems that once the refrigerant has condensed, it is much more successful in carrying the CNTs through the system, with minimal fouling. The middle third section of each condenser circuit was virtually devoid of CNTs, but the last third of each circuit did have a very small amount of nanoparticles stuck to their walls: as much as 1.6×10^{-6} grams per square millimeter (0.016 gr/in^2). Aside from that, the latter two-thirds of the condenser was unremarkable in terms of clinging CNTs.
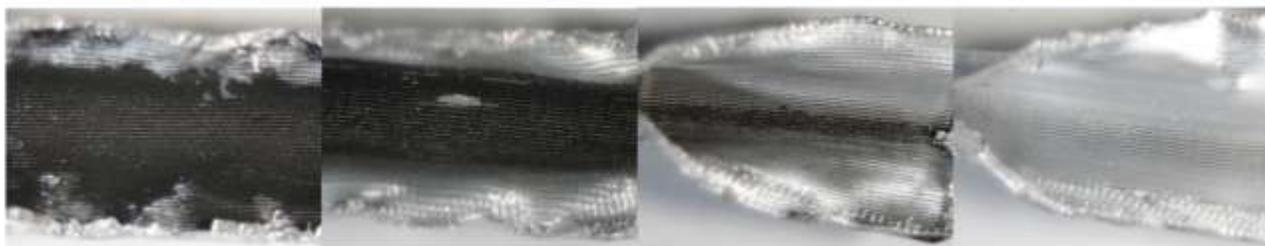

Figure 5. Condenser circuit one at 6 inches (0.15 m); 5 feet (1.5 m); 7 feet (2.1 m); and 10 feet (3.0 m). Each segment is approximately one inch (0.025 m) in length. The leftmost segment initially had complete circumference coverage; this coverage declined to a stripe before being completely devoid of CNTs.

The post-condenser manifold and the 2 feet (0.6 m) of 3/8 inch (9.5 mm) inside diameter copper tubing (including the 2nd quarter-turn ball valve) had no apparent adhered CNTs. In normal operation, this section of the system would be completely in the liquid phase so it does not seem surprising that no CNTs were left behind.

The thermal expansion valve was the next component to be investigated. The upstream two feet (0.61 m) of pipe had no CNT fouling. The inside of the valve was entirely coated with a light film of CNTs (Figure 6), as were the very small 3/32 inch (2.4 mm) inside diameter tubes

(downstream of the TXV) leading into the evaporator. The area density of these small tubes was about 7 x 10^{-6} grams per square millimeter (0.07 gr/in^2). This was a significant discovery because the tubes leading to the evaporator are very small and in time could have significant blockage with nanoparticles. This was the first low-pressure (i.e. relatively cold) location of the system where the CNTs were found stuck on the inside of the tubing walls.

Figure 6. View into the interior of the TXV.

The evaporator section was evaluated next. Based on what had been observed thus far, it was expected that the end of each evaporator circuit would provide the best possibility of CNT fouling (since the refrigerant would be a superheated vapor); however, this was not the case. In order to obtain a clear picture of the fouling tendencies, each of the five evaporator circuits was sampled at 12 locations along the length. It was found that the greatest concentrations of nanoparticles were at the beginning of each evaporator circuit. The CNTs were not as concentrated as they were at the beginning of the condenser circuits, but the first 3-4 feet (0.9-1.2 m) of each circuit could account for as much as 0.1 grams (1.54 grains) of clinging CNTs apiece. The area density in this area was approximately 8 x 10^{-6} grams per square millimeter (0.08 gr/in^2). Beyond 4 feet (1.2m), concentration of CNTs quickly decreased. In some of the mid-

evaporator circuits (i.e. middle third), there was no sign of CNTs; yet in other circuits, though not nearly as concentrated as the beginning of the evaporator, there were CNT deposits, as Figure 3 shows. It was not the case for every circuit, but in general, the latter third (~9 feet (2.7 m)) contained more CNTs than the middle third. The only consistency found in the evaporator was that the first few feet were moderately fouled in each circuit. The position of each circuit, and individual tubes, were cross referenced to each other to find if position in the evaporator influenced the fouling. No correlation was discovered. Figure 7 shows four samples from evaporator circuit three. This circuit is approximately the average in terms of the fouling at each point.
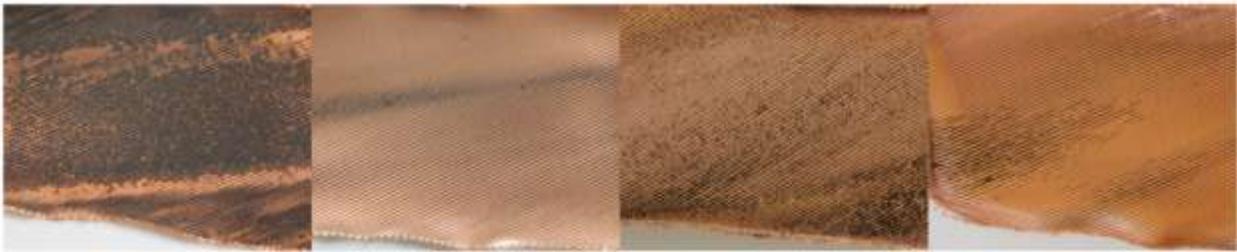

Figure 7. Images of inside tube surfaces from the third evaporator circuit. Left to right: 2 feet (0.61 m); 8 feet (2.4 m); 17 feet (5.2 m); and 26 feet (7.9 m). All measurements from inlet of the evaporator.

Five and one-half feet (1.7 m) of 5/8 inch (16 mm) inside diameter copper pipe and the last quarter-turn valve were located downstream of the evaporator and prior to the compressor inlet. This last 5.5 feet (1.7 m) had minimal CNT fouling. Also, this part of the system had a relatively large amount of POE oil on the inner tubing surfaces, as compared to the rest of the system. By observation, the section before the quarter-turn valve was ranked at '1' with negligible amounts of CNTs. After the valve, the amount of CNTs were found to be slightly higher and given a ranking of a '2'.

Lastly, the compressor was closely evaluated. After the compressor was disconnected from the system, the POE oil/CNT mix was poured out of the low pressure inlet; this was the same port used to insert the mixture into the compressor (Fig 2). The bottom section (i.e. low pressure portion) of the compressor was flushed with R-113 three times to remove as many CNTs as possible. On the third flush, the liquid refrigerant flush was clear. Next, the compressor's high pressure 'dome' was removed with a band saw. As can be seen in Figure 8, CNTs and oil coated the interior of the dome. To be in that location, they had to have come through the scroll assembly of the compressor, along with the refrigerant and oil. See table 2 for the mass of CNTs collected from the compressor's high pressure dome.

A second cut removed the scroll assembly from its motor and oil sump. There were traces of CNTs and oil in this area: on the motor windings, interior walls, and even inside the internal electrical connection. However, it cannot be definitively said that the pouring of the oil/CNT mix did not contribute to the CNT coating in this area of the compressor. On the other hand, the extent to which the dome was coated and the fact that so many CNTs were found throughout the system, clearly displays that nanoparticles can and do leave the scroll compressor during operation.

Figure 8. High pressure dome of the scroll compressor. A thick coat of CNTs and POE oil cover most of the dome.

As previously noted, the CNTs recovered from the system were weighed in order to obtain an indication of how many nanoparticles were outside of the compressor; how many had permanently fouled the interior tube, fittings, and compressor walls; and how many were incidental and still freely flowing within the system.

Of the six grams of CNTs placed in the compressor, only 2.47 g ± 0.12 g (38.1 grains ± 1.85 grains) were recovered from the compressor flush. Methanol flushes throughout the entire system yielded another 1.25 g ± 0.24 g (21.4 grains ± 0.37 grains). This implies there were approximately 2.28 g (33.2 grains) of CNTs that were left clinging strongly to the walls of the system.

DISCUSSION

Fouling Factors

CNTs were used in this work because they have shown very promising results in passive enhanced heat transfer tests. The literature also seemed to indicate that CNTs were resistant to

fouling on metal tubes within heat exchangers. Even if nanoparticles can initially improve heat transfer, long-term fouling and building up inside the heat exchanger could cause problems. Although Park et al. (2007a and 2007b) did not indicate fouling issues in their works, it is clear from the results of this study that CNTs will adhere to metallic heat transfer surfaces (copper, aluminum, brass, and steel).

The evaluation of heat transfer enhancements (such as CNTs) in a fully functional, commercially available air-conditioning system presents many different issues, as compared to a tightly controlled experiment. From a material standpoint, a complete system is more complex with various types and configurations -- enhanced heat transfer surfaces such as interior ribs in the evaporator and condenser sections present one factor. Confounded with that factor, at least in the condenser, is the material used. The only place in the entire system constructed from aluminum was in the condenser; the aluminum was also ribbed. This means there is no area in the system that has smooth aluminum surfaces. The small copper tubes leaving the pre-condenser manifold had no interior ribs; although there were a small amount of CNTs left on these small tubes, it could reasonably be considered negligible compared to the increase of adhered CNTs as soon as the aluminum section began. This dramatic increase cannot be attributed to the fact that these copper tubes are not intended to be a heat exchange surface, as they are in the path of the condenser fan's airflow and are effectively serving as the condenser's beginning. In this situation then, it is the aluminum material, the ribs, or both that cause the increase in fouling.

The ribs themselves do seem to have an effect on the amount of fouling that occurs. As a test of how tightly the CNTs were adhered to the interior of the heat exchanger surfaces, a brand new, hard bristled toothbrush was used in an attempt to remove small patches of clinging CNTs

that could not be removed with methanol flushes. The tips of the brush were darkened with carbon, but the amount removed from the surface was negligible. Because these nanoparticles were so tightly attached, there is clear potential that, over time, CNTs could continue to build up and impact heat transfer.

Another factor, vapor quality of the refrigerant, seems to be more definitive. Figure 4 shows the quick decline of clinging CNTs in the first ten feet of the condenser. It seems probable that as the refrigerant condensed, the CNTs were less and less able to adhere to the walls. While it seems intuitive that the thinning path of adhered CNTs would be toward the gravity bottom of the condenser circuit, this was not the case. Based upon the results of this experiment, it appears that the condensed, higher density, liquid refrigerant, which would be at the gravity bottom of each tube, helps keep the CNTs from fouling this portion of the tube. The latter two-thirds of the condenser, where vapor quality is expected to decline to near zero, was nearly devoid of CNTs (in stark contrast to the first two feet of the aluminum condenser). Furthermore, no CNTs were found in the tubing located between the condenser and TXV. This supports the hypothesis that less fouling occurs when refrigerant is a liquid, independent of material or tube enhancement type.

One other potential factor is refrigerant temperature. By comparing the smooth copper pipe (inside diameter: 1/2 in or 12.7 mm) between the compressor outlet and condenser (high temperature) with the smooth copper pipe (inside diameter: 5/8 in or 15.9 mm) between the evaporator and compressor inlet (low temperature), it was observed that the high temperature side contained more deposited CNTs, and at higher area densities (see Figure 3). Also, one methanol flush of the lower temperature copper tubes cleanly removed all CNTs, but the CNTs in the higher temperature copper tubes were much more resistant, requiring 3-4 flushes for

removal of non-adhered CNTs. Note that the previously mentioned pea-sized clumps of CNTs at the high temperature exit of the compressor could not be removed with methanol either.

All of these factors (pipe material, interior surface characteristics, vapor quality, and temperature) overlap to the point that it is not possible, from one trial, to rank the importance of their effect on fouling. It is, however, very clear that at least some of these factors can induce substantial fouling.

Progressive Fouling

If nanoparticles are to be used in a standard vapor-compression system with no modifications, a pressing question needs to be answered: Will the heavy fouling found in the first few feet of the condenser continue to progress farther and farther down the condenser line? The extent of the fouling found at the outset of the aluminum condenser, though not tested, seems to strongly indicate that heat transfer capabilities may be handicapped. The left side of Figure 9 shows a close-up (3 mm x 3 mm (0.12 in. x 0.12 in.)) of the fouling that is representative of the first few inches of each condenser circuit. The right side of Figure 9 shows a close-up of the same dimensions of the same circuit at 10 feet (3 m) into the circuit. Recall, based upon the entirety of the condenser, the fouling is strongest in the 100% vapor quality region and diminishes to virtually no fouling in the liquid refrigerant portion of the condenser. If the fouling inhibits heat transfer, phase change may occur later in the condenser, allowing nanoparticles a more favorable environment to adhere to the surfaces. This could cause a kind of 'snowball' effect, eventually fouling the entire length of the condenser and ceasing to properly condense the refrigerant.
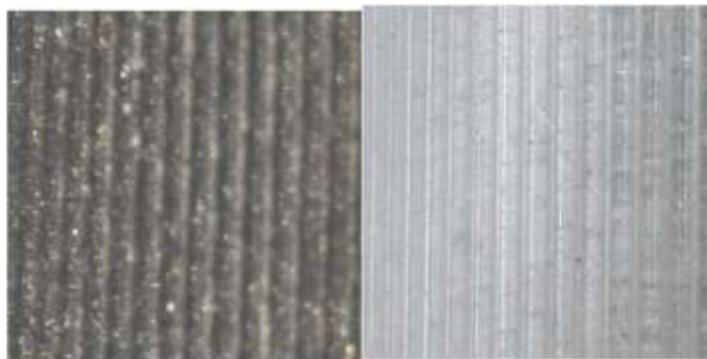
Figure 9.   Close-up comparison of 3x3 mm (0.118 in. x 0.118 in.) sections of condenser circuit one. Left: 6 inches (0.15 m) into the circuit; Right: 10 feet (3 m) into the circuit.

Dispersion of CNTs

Before this work, it had not been shown definitively that nanoparticles, if initially inserted into the compressor, would ever exit the compressor. This migration would seem likely if the nanoparticles were dispersed in the compressor oil as it is known that a small percentage of this oil circulates throughout a system. On the other hand, nanoparticles do have a finite sedimentary stability, so it was speculated that the CNTs might fall to the bottom of the oil sump and never have an opportunity to leave the compressor.

Ultrasonic devices are used to break nanoparticle agglomerations and disperse the nanoparticles throughout the host medium. As noted previously, one of these devices were used on the CNT/oil mixture in this work. Although the motion of a scroll compressor is not ultrasonic, it does vibrate at a relatively high frequency and certainly agitates whatever is within. As a consequence, it was hypothesized that this motion may enhance the nanoparticles sedimentary stability. This work utilized non-stop compressor operation, but even after a long period of inactivity, this compressor motion could possibly re-disperse the nanoparticles throughout the oil in the sump after they have settled to the bottom and possibly help break down agglomerations that formed while the nanoparticles were sedimented.

Clogging

Micro-particles could have similar increases in heat transfer capabilities but can cause "severe clogging problems" (Choi 1995). A major reason for the interest in nanoparticles is the belief that they will not cause these problems. Based upon the work presented here, it would seem that theory has merit in the larger diameter portions of a system, but could present problems after long-term use in the smaller sections.

The first smaller diameter tubes encountered, in this mapping research, were the individual copper tubes leading from the pre-condenser manifold that were soldered to the aluminum condensing circuit. This entire section presents a possible difficulty. The individual copper tubes from the manifold did have some tightly adhered CNTs which, after a long runtime, may start to cause congestion problems, but they were not as worrisome as the transition from copper tube to aluminum condenser. In order to braze the transition from copper to aluminum, a thin, 1 inch (25 mm) insert of the same inside diameter is used to connect the two sections. This collar, upon inspection, had a substantial amount of clinging CNTs as shown in Figure 10. This transition, along with the previously mentioned build up of CNTs in the condenser could pose a significant fouling/clogging problem in this region.

Figure 10. Image of CNT buildup on the one inch transition piece from copper tube pre-condenser manifold to aluminum tube condenser.

Another portion that may require attention with regard to clogging are the small, 3/32 inch (2.4 mm) inside diameter distributor tubes leading from the TXV to the evaporator. By observation, this distribution tubing section does not seem as potentially problematic as the aforementioned condenser transition section, but the small diameter of the tube and the fact that CNTs did lightly coat the walls seems to warrant some consideration.

Other clogging possibilities are associated with the large agglomerated sections of nanoparticles that became adhered to the walls suddenly breaking loose and flowing with the refrigerant. These agglomerations could threaten to clog the TXV and the small, 3/32 inch (2.4 mm) inside diameter tubes beyond. Over time, and many off-on cycles, the functionality of the system could be severely impaired or halted altogether. In addition, the liquid-line filter-dryer was removed for this experiment. In a fully functional system, the presence of a filter-drier would likely remove all CNTs that were freely flowing with the refrigerant and oil mixture. Additional research is needed to consider the impact of a liquid-line filter-drier.

Although nanoparticles may be more promising than micro-particles with respect to potential clogging, further understanding of CNT deposition is needed. If nanoparticles are adhering and building up in these small tubes, they will present the same long-term problem as micro-particles.

CNT Brittleness

CNTs have a vulnerability that other nanoparticles do not: they are relatively long and slender and can break down into smaller pieces. Ultrasonification of CNTs could break these nanoparticles into smaller pieces of carbon (Tung 2012); as could the rigors of continuously flowing through a refrigeration system.

A scanning electron microscope (SEM) was used in order to compare the CNTs that were gathered from the compressor after seven days in the system, against the CNTs that were ultrasonified and not used, and against the CNTs directly from the supplier (i.e., virgin CNTs). Figure 11 shows this comparison from left to right, respectively.
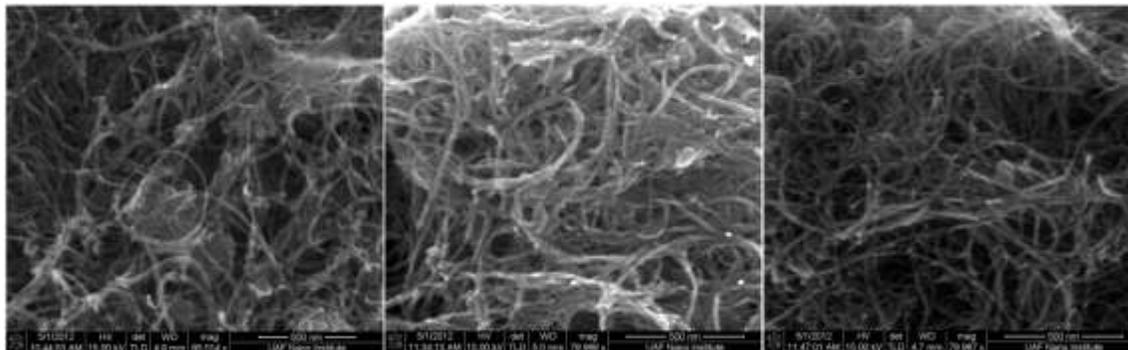

Figure 11. Scanning electron microscope (SEM) images of CNTs. Left to right: removed CNTs after the 168 hour system test; ultrasonified CNTs not used in system test; and virgin CNTs as purchased.

These SEM pictures show the CNTs as agglomerations, a consequence of the necessity to dry the samples before this type of electron microscopy image can be taken. Although direct, absolute comparisons cannot be made with these pictures, it can be said, with a high degree of

confidence, that ultrasonification and use in a system does not quickly break the CNTs down into significantly smaller pieces. Still, another question remains: How detrimental to heat transfer capabilities is it for CNTs to break apart, if at all?

CONCLUSION

In this work, a fully functional 2.5 ton (8.79 kW) air-conditioning system was used as a platform for an experimental study to map CNT movement and fouling potentials when charged with a refrigerant, oil, and CNT mixture. The system was operated continuously for 168 hours. The following conclusions to this study were as follows:

- CNTs mixed with POE oil and placed in the scroll compressor of a refrigeration system will exit the compressor and travel throughout the system. Not being previously discussed in the literature, this result was expected, but not to the extent observed.

- CNTs, when dispersed in refrigerant in vapor phase, will potentially foul the walls of aluminum, ribbed condenser tubes over time. The potential for significant fouling and/or clogging exists. Though seemingly not as severe, CNTs will foul inside surfaces of smooth brass and helical copper finned tubes, while the vapor quality is less than 100%.

- Only 2.5 grams (38.6 grains) of the original six grams of CNTs placed in the compressor could be recovered. Some of the remaining, approximately 3.5 grams (54 grains) of CNTs spread throughout the system, were still actively flowing with the refrigerant; but a large percentage of these CNTs had become strongly adhered to the walls of the system. Thus, there is strong potential for all CNTs to become fixed throughout the system over time.

FUTURE WORK

This work provided insight into operating a fully functional unitary air-conditioner with a mixture of refrigerant, oil, and nanoparticles. This was the first known work of its kind, so many questions and few answers resulted. It has shown that CNTs travel throughout the system. It has also highlighted the need for much more research to be completed before nanoparticles can reliably be used over a long period of time as a potentially passive heat transfer enhancement technique. CNT fouling, clogging of small passageways and sedimentation of nanoparticles in the compressor are among the more important areas in need of further investigation. In addition, it may be helpful for this work to be duplicated, but with a much longer run-time. For this project, the system was operated continuously for only seven days (168 hours), and identified several areas that warrant further research that include both applied and bench-top experiments.

One of these areas is the previously mentioned possibility of progressive fouling of CNTs in the condenser. The results of this experiment showed that by ten feet into the condenser circuits there was almost no deposition of CNTs on the inner tube surfaces. An investigation needs to be conducted to learn whether or not the fouling in the condenser will continue to extend farther into each circuit over a longer period of time. Another reason for further exploration using a longer run time is the potential for clogging. The transition to the condenser and the first few inches of the condenser, as well as the small tubes leading from the TXV, needs to be investigated and compared to this work.

As previously noted, it is a good possibility that CNTs will break down during ultrasonification and usage in a system. SEM pictures of CNTs collected from the compressor after a long run-time could show if this CNT breakdown is an actuality. If an extended run-time does break down the CNTs into much shorter segments, and if CNTs are to be used in future

vapor-compression systems, CNTs should be broken down by extensive ultrasonification and tested for fouling and HTC improvements.

An effort to determine the factors influencing the CNT fouling, both duplication of experiments and component-level experiments are recommended. Tests with temperature and pressure sensors, placed throughout the system to acquire surface temperatures of the compressor shell, condenser, and evaporator might provide insight. An abnormal increase or decrease in compressor temperature could indicate a change in friction characteristics. The friction characteristics of the compressor, while using nanoparticles, has been discussed in other works with nanorefrigerants (Wang and Xie 2003; Bi et al. 2008; Bi et al. 2011). Temperature and pressure measurements in the heat exchangers could provide insight into where the refrigerant condenses and evaporates. This is of utmost importance because it is unknown whether fouling from nanoparticles delays the condensing and/or evaporation process.

As mentioned in the 'Discussion' section of this paper, the effect of compressor agitation may serve as a substitute for the ultrasonic effect. In a real world vapor-compression system, the compressor will cycle on and off. Sometimes these shut downs can span a period of several months. During these periods of inactivity, nanoparticles in the compressor would certainly sediment to the bottom of the oil sump. The compressor may reverse this upon re-activation. In order to utilize nanoparticles in a conventional method such as adding them to the compressor and allowing the nanoparticles to travel throughout a system, the potential of the compressor to redistribute the nanoparticles needs to be investigated. So, tests that investigate the impact of on/off cycling are needed.

As can be seen from Figure 4, fouling tendencies were higher in the condenser and evaporator. While both heat exchangers in this study utilized inner enhanced surfaces (ribbed

38

tubes), a thorough series of experiments investigating the evaporation and condensation characteristics at standard operating conditions is needed for all combinations of tube material and type (e.g., aluminum and copper tubes; smooth and enhanced surfaces). Small sections of the heat exchangers that could be removed and replaced with new portions during an experiment such as this one would provide considerable insight into the rate at which CNTs will foul the interior of each heat exchanger. Another alteration to the system would be the addition of a port that allowed for extractive sampling immediately after the condenser. Small samples taken of liquid refrigerant intermittently over the course of the experiment would reveal the approximate amount of CNTs flowing with the refrigerant. This would provide 2 possible indicators: the CNT/refrigerant percentage flowing throughout the system; and any reduction over time of this percentage due to fouling. Because heat transfer experiments utilizing nanorefrigerants reference the percentage of nanoparticles used, it is important to know at what percentage nanoparticles are present relative to the refrigerant in an actual vapor compression air conditioning system.

REFERENCES

Berber, S., Kwon, Y., and Tomanek, D. 2000. Unusually high thermal conductivity of carbon nanotubes. *Physical Review Letters* 84(20):4613-6.

Bi, S., Shi, L., and Zhang, L. 2008. Application of nanoparticles in domestic refrigerators. *Applied Thermal Engineering* 28:1834-43.

Bi, S., Guo, K., Liu, Z., and Wu, J. 2011. Performance of a domestic refrigerator using TiO_2-R600a nano-refrigerant as working fluid. *Energy Conversion and Management* 52:733-7.

Buongiorno, J. 2006. Convective transport in nanofluids. *Journal of Heat Transfer, Transactions of the ASME* 128:240-50.

Choi, S. 1995. Enhancing thermal conductivity of fluids with nanoparticles. *Developments and Applications of Non-Newtonian Flows* MD-66:99-103.

Choi, S. 2009. Nanofluids: From vision to reality through research. *Journal of Heat Transfer, Transactions of the ASME* 131:1-9.

Das, S., Putra, N., and Roetzel, W. 2003. Pool boiling characteristics of nano-fluids. *International Journal of Heat and Mass Transfer* 46:851-62.

Ding, G., Peng, H., Jiang, W., and Gao, Y. 2009. The migration characteristics of nanoparticles in the pool boiling process of nanorefrigerant and nanorefrigerant-oil mixture. *International Journal of Refrigeration* 32:114-23.

Ding, Y., Alias, H., Wen, D., and Williams, R. 2006. Heat transfer of aqueous suspensions of carbon nanotubes (CNT nanofluids). *International Journal of Heat and Mass Transfer* 49:240-50.

Eastman, J., Choi, S., Yu, W., and Thompson, L. 2001. Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles. *Applied Physics Letters* 78(6):718-20.

Godson, L., Raja, B., Lal, D., and Wongwises, S. 2010. Enhancement of heat transfer using nanofluids-An overview. *Renewable and Sustainable Energy Review* 14:629-41.

Jiang, W., Ding, G., and Peng, H. 2009. Measurement and model on thermal conductivities of carbon nanotube nanorefrigerants. *International Journal of Thermal Sciences* 48:1108-15.

Jiang, W., Ding, G., Peng, H., Gao, Y., and Wang, K. 2009. Experimental and model research on nanorefrigerant thermal conductivity. *HVAC&R Research* 15(3):651-69.

Jiang, W., Ding, G., Peng, H., and Hu, H. 2010. Modeling of nanoparticles' aggregation and sedimentation in nanofluid. *Current Applied Physics* 10:934-41.

Johnson Controls. 2009. General Piping Recommendations and Refrigerant Line Length for Split-System Air Conditioners and Heat Pumps. www.usair-eng.com/pdfs/long-line-piping.pdf.

Jwo, C., Jeng, L., Teng, T., and Chang, H. 2009. Effects of nanolubricant on performance of hydrocarbon refrigerant system. *Journal of Vacuum Science and Technology B* 27(3):1473-77.

Kedzierski, M. 2009. Effect of CuO nanoparticle concentration on R134a/lubricant pool-boiling heat transfer. *Journal of Heat Transfer, Transactions of the ASME* 131:1-7.

Liu, D., and Yang, C. 2007. Effect of nano-particles on pool boiling heat transfer of refrigerant 141b. *Proceedings of the Fifth International Conference on Nanochannels, Microchannels and Minichannels, Puebla, Mexico*:789-93.

Park, K., and Jung, D. 2007a. Boiling heat transfer enhancement with carbon nanotubes for refrigerants used in building air-conditioning. *Energy and Buildings* 39:1061-4.

Park, K., and Jung, D. 2007b. Enhancement of nucleate boiling heat transfer using carbon nanotubes. *International Journal of Heat and Mass Transfer* 50:4499-502.

Peng, H., Ding, G., Jiang, W., and Gao, Y. 2009. Heat transfer characteristics of refrigerant-based nanofluid flow boiling inside a horizontal smooth tube. *International Journal of Refrigeration* 32:1259-70.

Peng, H., Ding, G., and Hu, H. 2011. Migration of carbon nanotubes from liquid phase to vapor phase in the refrigerant-based nanofluid pool boiling. *Nanoscale Research Letters* 6:219.

Trisaksri, B., and Wongwises, S. 2009. Nucleate pool boiling heat transfer of TiO_2-R141b nanofluids. *International Journal of Heat and Mass Transfer* 52:1582-8.

Tung, S. University of Arkansas, Mechanical Engineering Department, Fayetteville, AR. Personal Communication. April, 2012.

Wang, R., and Xie, H. 2003. A refrigerating system using HFC134a and mineral lubricant appended with N-TiO_2(R) as working fluids. *Proceedings of the 4th international symposium on HVAC, Tsinghua University.*

Wen, D., and Ding, Y. 2004. Experimental investigation into convective heat transfer of nanofluids at the entrance region under laminar flow conditions. *International Journal of Heat and Mass Transfer* 47:5181-8.

Wen, D., Lin, G., Vafaei, S., and Zhang, K. 2009. Review of nanofluids for heat transfer applications. *Particuology* 7:141-50.

Wu, D., Zhu, H., Wang, L., and Liu, L. 2009. Critical issues in nanofluids preparation, characterization and thermal conductivity. *Current Nanoscience* 5:103-12.

CONCLUSION

In this work, a fully functional 2.5 ton (8.79 kW) air-conditioning system was used as a platform for an experimental study to map CNT movement and fouling potentials when charged with a refrigerant, oil, and CNT mixture. The system was operated continuously for 168 hours. The following conclusions to this study were as follows:

- CNTs mixed with POE oil and placed in the scroll compressor of a refrigeration system will exit the compressor and travel throughout the system. Not being previously discussed in the literature, this result was expected, but not to the extent observed. In order to take advantage of the potential heat transfer improvement that previous researchers have discovered using nanorefrigerants, it is imperative that nanoparticles make their way to the heat exchangers (i.e. evaporator and condenser) in a vapor compression system. This study showed that CNTs do migrate to these heat exchangers.

- CNTs, when dispersed in refrigerant in vapor phase, will potentially foul the walls of aluminum, ribbed condenser tubes over time. The potential for significant fouling and/or clogging exists. Though seemingly not as severe, CNTs will foul inside surfaces of smooth brass and helical copper finned tubes, while the vapor quality is less than 100%. While it was found that CNTs will move into the heat exchangers, a positive finding, this fouling may have a negative net impact on heat transfer in these heat exchangers.