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Experimental Study on the Palatability Impacts of Potable Water as a Hydronic Medium

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Received: 17 January 2018; Accepted: 14 February 2018; Published: 17 February 2018

Abstract: Hydronic systems installed in buildings utilize water to transport thermal energy within the building for heating and cooling purposes. These systems can be closed loop, where the water is chemically treated and circulated indefinitely, or they can be open loop, where the water is not treated and is effluxed as a result of occupant activities, such as bathing or cooking. Water in an open loop system may circulate within the system for a limited time before it is extracted from the system by occupant activities and replaced with new water from the local water supply. The implementation of open loop hydronic systems is becoming more common in multi-unit residential buildings, even though a number of questions regarding the use of such systems remain unanswered. One concern regarding the use of circulated potable water for heating purposes is the potential effects on the occupant perceptions of the palatability of the service water being delivered to their suites. In an open-loop HVAC system (Heating Ventilating, Air Conditioning System), heating water is subject to repeated thermal cycles and continuous recirculation, which creates the potential for chemical alterations of the materials present in the water or leaching of materials from the equipment and piping. Through the use of Flavor Profile Analysis (FPA) established by the American Water Works Association, and a multi-unit HVAC system constructed in a controlled environment, the palatability effects of the operational system were evaluated for a number of scenarios. The collected feedback from the study participants was then tabulated to quantify the impacts of using potable water as a recirculating heating medium on the perceptions of the occupants. The resulting observations led us to conclude that utilizing potable water as a heating medium has a negligible effect on the palatability of water in the system for average retention times under one day, and a non-objectionable, but noticeable, effect for higher average retention times.

Keywords: palatability; open-loop HVAC; occupant perceptions

1. Introduction

It is common for multi-unit residential buildings to be constructed with a central heating plant to provide for the servicing requirements of the building. Buildings which utilize a central system will typically employ multiple systems and distributions due to the different servicing needs of the suites, which can include heating water, potable hot service water, potable cold service water, and chilled water. It is not unusual for these systems to be installed using completely separate piping systems, even though similar materials are being transported. This involves the installation of multiple piping systems which convey similar materials intended for differing purposes, specifically hot water for building heating and hot service water for occupant consumption. In a building where cooling is provided, this could result in up to seven pipes being required to connect the central mechanical system to the suites; heating water supply (closed loop), heating water return (closed loop), cooling water supply (closed loop), cooling water return (closed loop), potable hot service water supply (open loop), potable hot service water return (open loop, used to circulate the hot water and maintain the temperature of the system), and potable cold service water supply. As the material being transported is similar, all pipes are transporting hot or cold water; the piping can be combined into a single distribution system able to fulfill the requirements of both uses, provided that all local codes and safety standards for heating by potable water have been met.

The technique of using potable water as a hydronic medium in multi-unit residential buildings involves the utilization of heated service water as the thermal transport medium for conditioning the building environment. In what is often referred to as an "integrated piping system" [1] or a "combination system" [2], hot service water is delivered to the heated areas using the potable water distribution system that has been installed within the building. This system only requires four pipes: potable hot service water supply (open loop to deliver heating water and water for consumption); potable hot service water return (open loop, returns heating water back to the mechanical system); potable cold service water supply (open loop to deliver cooling water and water for consumption); and potable cold service water return (open loop, returns cooling water back to the mechanical system). In the suites, a portion of the delivered water is used by the occupants as a part of their consumption for daily activities, including bathing and cooking, while the remaining portion is recirculated back to a central plant after being utilized to condition the space. Such systems do not utilize chemical treatment and must be fully constructed out of materials suitable for use with potable water, as the water is still considered potable and suitable for occupant use. While the concept of using potable water as a heating medium in single-family dwellings has been investigated in a number of studies [3,4] with a number of documented advances in efficiency, the investigation and implementation of this technique in multi-unit residential buildings has been limited. Due to this lack of investigation, there have been concerns raised about the implementation of these systems from both performance and safety standpoints [5,6].

One major concern explored within this paper is that the utilization of potable water for HVAC, particularly heating, may alter the water due to trace materials in the water being exposed to cycles of heating and cooling, or due to materials from the system itself leaching into the water. This has the potential to result in tastes or odors that occupants would find objectionable [7–10]. Given that taste and odor are considered two of the most important criteria for potable water systems [11], and are often used as an indicator of water safety [12], this is of interest to designers and manufacturers.

This paper describes an experimental design constructed to simulate a to-scale multi-unit residential building through which water samples are generated to represent a range of simulated occupant behaviors. By altering the daily consumption of the simulated occupants, the retention duration of the water within the system was varied. This permits the generation of samples with retention times or consumption ratios (CR, the ratio of system volume to daily occupant consumption) which are larger than those commonly encountered outside a controlled environment. Samples collected were presented to a group of trained panelists, who tested and rated the samples in accordance with the Flavor Profile Analysis (FPA) procedure provided by the American Water Works Association [13]. Flavors and intensities are tabulated and compared to determine if any tastes reported in the samples are attributable to how long the water was in the HVAC system.

2. Materials and Methods

2.1. Experimental Design

To effectively study the impacts on the palatability of potable water when implementing potable water heating distribution in a building, a potable water mechanical system was constructed in a controlled environment which would be used to generate water samples for analysis. The completed system was modeled on a 4-unit apartment building in a riser configuration that is capable of delivering heating, cooling, and service water to each unit as depicted in Figure 1. The author selected the riser configuration for this case because it is representative of many low-rise residential buildings that are constructed with a central heating plant. Water is sent by plumbing from the central plant to each suite, where it can be delivered to the unit's plumbing fixtures or circulated through a potable-rated fan coil (heat exchanger) and returned to the central plant for re-conditioning. All components utilized in the construction of the apparatus are rated for use with potable water, and all piping in the apparatus constructed was configured in a manner that permitted circulation of all components every 24 h in accordance with local codes [14] to prevent stagnation. The apparatus is controlled by a programmable logic controller (PLC), programmed to operate control valves and actuators to control heating/cooling cycles and to simulate occupant activities that consume potable water. This enables the operator to tightly control the apparatus and allow the system to produce samples under strict conditions. The materials utilized in the construction of the apparatus include PVC for cold water distribution, cPVC for hot water distribution, PEX tubing for terminal unit connections and fixture connections, copper inside the fan coils, and brass and bronze fittings. This is significant as many of these materials have been tested for palatability impacts individually [8,15,16]; there has not been a study of a completed system using these materials together.

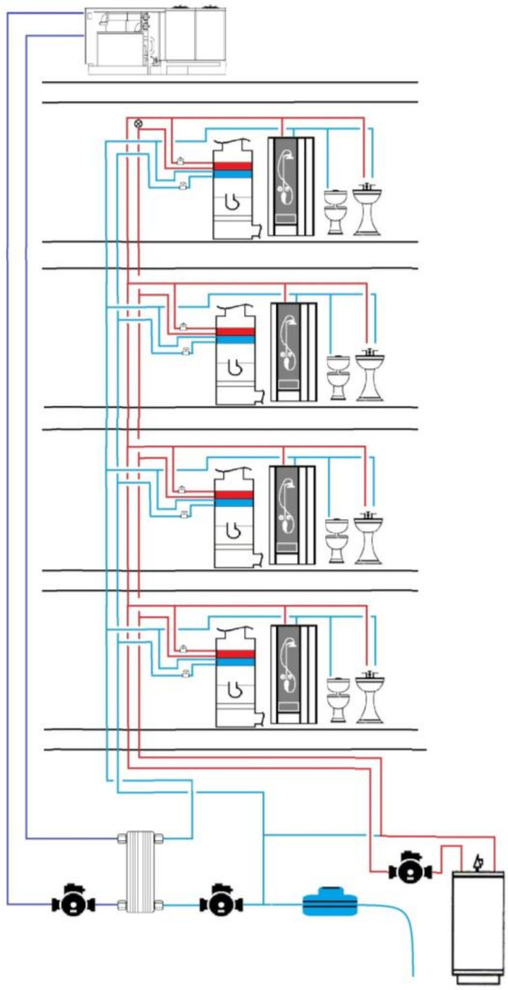

Figure 1. A schematic representation of the potable water HVAC apparatus constructed to generate samples. The apparatus includes four independently controlled 4-pipe fan coils, four suite distribution headers, one hot water generator, and one chilled water system.

2.2. Water Palatability Test Protocol

The desirability of water is largely governed by taste, a subjective trait which can be difficult to quantify. Since the evaluation of the palatability of potable water is routine for the municipal water works industry, AWWA has developed a set of procedures referred to as "Standard Methods", which includes Standard Method 2170 B–FPA [13]. Standard 2170 B includes the procedures for conducting a Flavor Profile Analysis (FPA) and has been used successfully for establishing flavor characteristics and associated intensities in water samples [17]. According to the outlined standard methods, the FPA utilizes a group of screened panelists, 4 to 6 per panel visit in this study, to evaluate samples of water and provide a single description and intensity for each sample. Intensities are assigned a numerical value by each panelist in accordance with the FPA procedure, ranging between 0 (no taste) and 3 (objectionable, not drinkable) in 0.25 increments (threshold of detection per FPA), providing a quantitative measurement for flavor. An intensity of less than 1 (but greater than 0.25) is considered to be noticeable, but not objectionable, and an intensity of 1 or greater is considered to have the potential to be objectionable. Screening and training of the panelists includes testing volunteers for the ability to distinguish taste and intensity of pre-determined flavor samples in accordance with Standard Method 2170 B.

Once the panelists have been selected, additional screening is conducted throughout the experiment to evaluate the panel members' consistency when evaluating tastes. This is done by conducting flavor profile sessions where apparatus test samples are not provided and identical source water samples are included in the sample set. The data collected from participants who report a variation beyond the threshold of detection in these samples as provided in the procedures for Standard Method 2170 B are excluded from the analysis. This extra level of screening is above the prescribed requirements of Standard Method 2170 B, but was considered valuable for maintaining the consistency of the results.

Previous investigations into water palatability have encompassed issues such as the effects of the water's age on active municipal distributions [18], and the use of FPA to study the effects of piping materials on the palatability of potable water [16]. In each study, the effects on palatability of the reviewed variable have been found to be minimal under the operating conditions adopted in the present study, where the age of circulated cold water as well as certain piping materials in the cold water system are not considered among the uncontrolled variables. Accordingly, this study focuses on the potable hot water used in the system.

A total of four samples is provided in random order for each evaluation meeting to prevent any bias by the participants and to provide a variety of samples:

1. Apparatus water, hot service water samples from the building system at the point of use by the simulated occupants.
2. Potable cold supply water from the municipal supply feeding the apparatus.
3. Potable hot water from an adjacent, traditional source. This source was supplied with the same cold supply water as the apparatus, but the water was not used for HVAC purposes.
4. Commercial bottled water (Nestle Pure Life purified water).

While the apparatus water and the cold supply water are the samples of interest, control samples from other sources are provided to allow for additional comparisons to identify possible causes for flavor variations. Each sample is collected at the same time from the service water discharge of the apparatus and thermally stabilized to 25 °C in accordance with Standard Method 2170 B. The four samples are evaluated by the panel and the results are compared to determine if there are any effects which could be attributed to the use of potable water for heating purposes.

In addition to the samples collected for the FPA, additional samples of Apparatus Water, Potable Cold Supply Water, and Potable Hot Supply Water are collected for laboratory analysis to identify potential chemical alterations which would be correlated to any reported FPA results. While this does not provide definitive proof of cause of the flavor alterations, it allows for certain variations to be eliminated as probable contributors.

To evaluate the repeatability of the tests, the panel tests are repeated again after one year with the same apparatus and different panelists. While participants are allowed to volunteer for both sets of evaluations, the screening and recruitment process was completely repeated in full to encourage different individuals to participate in the panel study. The first panel test includes a single panel of volunteers which meets on a weekly basis for approximately three months. The second panel test expands the volunteer group to include three to four panels of four volunteers each of which meets weekly for approximately three months.

2.3. Apparatus Samples

Throughout the FPA, the dependent variable is the descriptor intensity as evaluated by the panel, between the water samples generated by the experimental apparatus and the water samples derived from the feed water supplying the experimental apparatus. The independent variable is the consumption ratio (Cr) of the experimental apparatus:

$$CR = Sv/Oc \tag{1}$$

where CR is the consumption ratio (days); Sv is the system volume; Oc is the occupant daily consumption.

In this equation, the consumption ratio (CR) refers to the representation of the variable being investigated; the system volume (Sv) refers to the volume of the distribution system including all vessels, pipes, and fittings; and the occupant consumption (Oc) refers to the volume of water consumed by the simulated occupants each day.

All samples were collected one day prior to the panel meeting. The samples were then temperature-stabilized during this time period in accordance with the testing protocol [13] and held in the same location in order to eliminate any variations in temperature or environmental impacts that may generate undocumented variations between the samples. Samples were stored in Teflon sealed glassware in accordance with the testing protocol.

In existing multi-unit residential potable water heating distributions, it should be noted that consumption ratios of less than one, where the daily consumption by occupants is greater than the volume of the distribution system, are typical, with the authors not being aware of any reported palatability concerns. Samples with consumption ratios greater than 1 are thus considered in this study. Elevated consumption ratios are possible in practice due to the large system volumes present in multi-unit residential buildings and low consumption, either due to water-efficient design or low occupancy. To generate the samples, the experimental apparatus is allowed to operate automatically for time periods of no less than one week per unit of consumption ratio to simulate long-term operation. Due to the time required, samples are limited to consumption ratios ranging from 1 to 7.

3. Results and Discussion

3.1. Palatability Results

While the intent is to compare the reported flavor of the apparatus water to the source supply in order to investigate alterations, other observations are identified during the FPA studies that provide insight into the causes of the flavor alteration. First, any flavor variations between the cold supply water and the bottled water control samples (sample item 2 and sample item 4) are reported by the panels to be below the threshold level. This is consistent with prior research on tap water and bottled water flavor comparisons [19]. Second, any flavor variations between the cold supply water and the potable hot water samples (sample item 2 and sample item 3) are also reported by the panels to be below the threshold level. This is significant, as any chemical variations between sample 2 and sample 3 can be eliminated as sole contributors to variations in sample flavor.

Regarding the comparisons between the apparatus water and the cold supply water samples (sample item 1 and sample item 2), the most commonly reported descriptors among the panel groups are found to be chlorinous, chalky, and bitter. Given that the variable being measured is the change in intensity of flavors between the apparatus water and the supply water, the numerical representation of the intensity of any flavor reported for the supply water is removed from the intensity of any reported flavor of the apparatus sample; the resulting intensities for each panel group are compiled and shown in Figure 2. From the resulting intensities, consumption ratios in excess of 1 indicate changes in the perceived flavor of the water that are objectionable. While reviewed consumption ratios as high as 7 are found to result in noticeable changes to the intensity of reported flavors, under none of the consumption ratios tested does the panel report that the change in flavor is in the objectionable range. Additionally, both panel tests produce results with similar outcomes, which implies that a similar mechanism is affecting the palatability of the water independently of the time elapsing between tests.

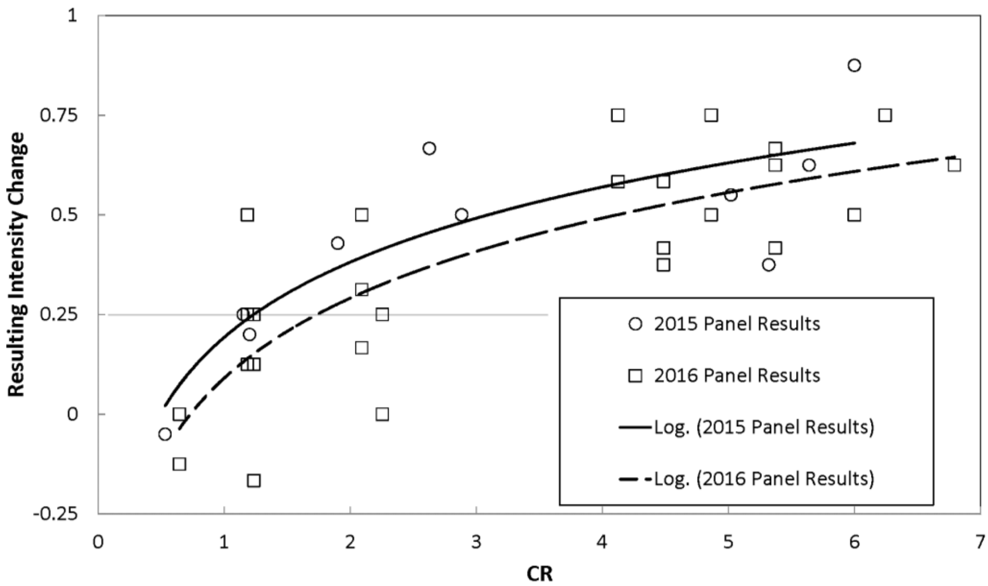

Figure 2. Changes in panel-recorded taste intensities between apparatus samples and source water samples.

3.2. Chemical Analysis Results

Samples were collected for chemical analysis to review potential changes in the chemistry of the water that could hypothetically contribute to the panelist's perception of the water. Samples were tested by a laboratory accredited in accordance with ISO/IEC 17025:2005.

Chloramines/Chlorine. Chlorine is not found in any of the analyzed apparatus water tests. There is a consistent measured increase in chloride and ammonia for all collected samples, which suggests that the total chlorines have reduced to simpler components as shown in Table 1. This is not unexpected, as it has been previously indicated that heated storage with recirculation will reduce the chlorine content and promote the formation of disinfection by-products [20]. The potential contribution to the palatability should be further explored since the reduction in chlorine presence is found to be absolute for all CRs rather than being correlated with reported intensities.

pH, conductivity, alkalinity, TDS (total dissolved solids), hardness, nitrate/nitrite. All samples report minimal changes between the cold source and apparatus samples for the above-identified parameters as depicted in Table 1. These changes are not considered significant as the variation in measured readings among the cold source samples varies more significantly through the test period than the difference between the cold supply samples and the apparatus samples for any individual test.

Major ions and dissolved metals. While the mass spectrometry tests test for the presence of over 40 elemental metals in the water, only a small number indicate a material change in concentrations. Many of the metals, including copper, lead, manganese, and silver, identified an increase in concentration relative to the source sample but with the increase being constant for all tests and not varying with the consumption ratio for all CRs tested, which suggests a lack of independent influence on the palatability of the water. This is significant as the study of thermal variation causing thermogalvanic corrosion in copper pipes has been well documented, but it does not appear to be a contributor to the alterations in palatability of the potable water [21]. Five elements that were included in the analysis exhibit a measurable increase, which correlates to the CR of sampling; boron, cadmium, cobalt, lithium, and zinc, as shown in Figure 3. These metals are recognized as present in commonly used plumbing components and the majority of the materials are measured well below acceptable levels, with the potential exception of cobalt. While cobalt is accepted in drinking water without standards in place in most jurisdictions, three U.S. states (Arizona, Minnesota, and Wisconsin) have guidelines in place for cobalt levels in drinking water [22,23]. Although they are guidelines and not standards, it should be noted that for longer duration CR values in the present study, these guidelines are found to be approached or exceeded. The measured concentrations are not high by any means [24], just approaching or exceeding the few existing guidelines that are available. The source of the cobalt in this study could be difficult to isolate, although it should be noted that cobalt oxide is used as a binding agent for the glass lining of glass-lined storage tanks and water heaters.

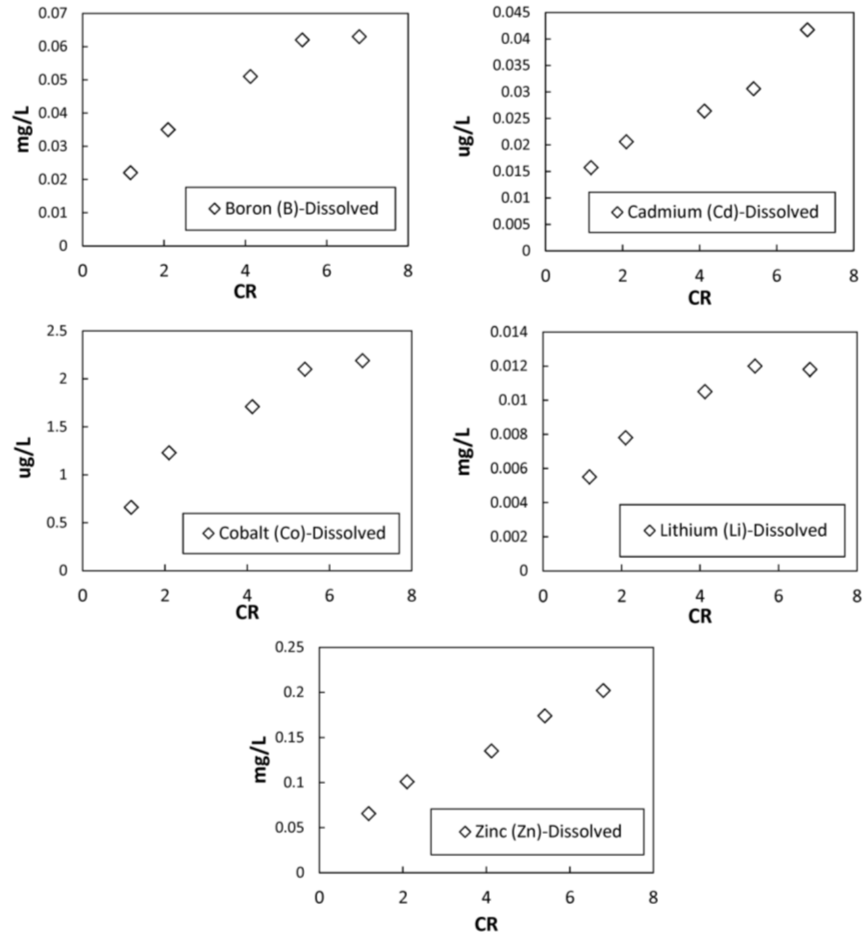

Figure 3. Dissolved metal increases relative to the consumption ratio.

Table 1. Chemical results which did not exhibit material chemical changes due to the apparatus or expected changes which were shown to not impact the palatability results.

	Detectable Limit	Units	Source Water Average Chemistry	Min	Max	Apparatus Water Average Chemistry	Min	Max
Chloramines								
Chlorine, Free	0.1	mg/L	0.468	0.1	0.74	0	0	0
Chlorine, Total	0.1	mg/L	1.116	0.13	1.84	0	0	0
Total Chlorine minus Free Chlorine	0.2	mg/L	0.805	0.38	1.54	0	0	0
Ammonia, Total (as N)	0.05	mg/L	0.3296	0.308	0.349	0.4362	0.416	0.453
Chloride (Cl)	0.5	mg/L	5.066	4.78	5.58	5.888	5.59	6.26
Fluoride (F)	0.02	mg/L	0.6712	0.655	0.693	0.759	0.743	0.796
Ion Balance		%	98.28	96.3	99.2	98.22	96.4	99.7
TDS (Calculated)		mg/L	212.8	205	220	208	200	220
Hardness (as $CaCO_3$)		mg/L	168	162	172	162.6	157	173
Nitrate (as N)	0.02	mg/L	0.0498	0.022	0.074	0.0572	0.03	0.079
Nitrate and Nitrite (as N)	0.022	mg/L	0.05675	0.045	0.074	0.0572	0.03	0.079
Nitrite (as N)	0.01	mg/L	0	0	0	0	0	0
Sulfate (SO_4)	0.3	mg/L	68.32	64.3	72.1	66.76	64.8	68.9
pH	0.1	pH	8.134	8.01	8.2	8.112	8.08	8.16
Conductivity (EC)	0.2	uS/cm	396.2	384	410	389.2	375	405
Bicarbonate (HCO_3)	5	mg/L	140	131	147	135	128	145
Carbonate (CO_3)	5	mg/L	0	0	0	0	0	0
Hydroxide (OH)	5	mg/L	0	0	0	0	0	0
Alkalinity, Total (as $CaCO_3$)	2	mg/L	115	108	121	110.6	105	119

4. Conclusions

In a system where potable water was continuously circulated as a hydronic heating medium and not allowed to become stagnant, the perception of the potable water used was not affected to such an extent that individuals consistently reported an unsatisfactory alteration in taste for the range of consumption ratios tested. A consumption ratio in excess of two was required for consistent reporting of any perceptible change in the taste intensity present in the water samples. Based on these results, it would be recommendable to maintain a consumption ratio of one or less for systems utilizing potable water as a hydronic heating medium, regardless of the circulation procedures of the system as a whole. Chemical testing was able to identify metallic leaching of specified elements into the system water which did correlate with changes in flavor descriptor intensity of the water, and while the concentrations are low, these likely contributed to the flavor of the water individually or in combination. Under no consumption ratios did any of the metallic concentrations indicate an unsafe accumulation.

Acknowledgments: Funding was provided through the Engineered Air Fellowship for HVAC Research. Engineered Air did not participate in the design, collection, analysis, or interpretation of the data.

Author Contributions: Robert Prybysh and Jeremiah Osolu conceived and designed the experiments. Robert Prybysh performed the experiments. Robert Prybysh analyzed the data. Mohamed Al-Hussein and Brian Fleck contributed materials. Robert Prybysh, Mohamed Al-Hussein, Brian Fleck, and Mohtada Sadrzadeh wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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