EVAPORATIVE COOLING CONDENSER FOR AIR-CONDITIONING
Team EVCO
University of Texas at Tyler, Texas, USA

Mission Statement

Our mission is to significantly improve energy savings and reduce CO_2 emissions in existing air conditioning systems by proposing a new concept that will be beneficial to individuals, society, and the earth we all share.

Team Members Biography

Amrit Thapa is a graduate student in the Department of Mechanical Engineering at the University of Texas at Tyler. He completed his bachelor's degree in Mechanical Engineering in 2021. As an undergraduate student, he worked on different energy-related projects like designing an axial fan for high efficiency, designing an electric Unmanned Aerial Vehicle (UAV), etc. He is interested in research to develop innovative technologies to decarbonize our society, combat climate change and its impacts, and enable safe, affordable, clean, sustainable energy.

Kristinoba Olotu obtained her bachelor's degree in Chemical Engineering and is currently a graduate student in the department of Mechanical Engineering at the University of Texas at Tyler. Her current work as a graduate research assistant is focused on the development of alternative energy. Having acquired over four years of work experience as a Drilling Engineer in the oil and gas industry, the wake of the global energy crisis spurred her to want to make her contribution towards a greener earth and the net zero goal by returning to graduate school as an energy researcher. As the world takes strides in building a more sustainable and secure energy future and being fully aware of the timeframe for the world to fully transition to sustainable energy forms from fossil fuels, she is interested in reducing carbon footprints as it affects climate change, this is her motivation for participating in the Jump to Stem Challenge. In the future, she hopes to own her renewable energy company, which powers underdeveloped communities by harnessing energy from waste materials.

Oluwanisola Makinde is a graduate student in the department of Mechanical Engineering at the University of Texas at Tyler. His experience in a 3rd world country, Nigeria, shaped his perspective on energy and the built environment. As a young child with an inquisitive mind, he always wondered why the major source of electricity is from fossil fuels, with the major drawback being CO_2 emissions. This challenge aroused his interest to collaborate and delve into how sustainable technologies can reduce emissions and climate impact and preserve the environment. His career goal is to be a research scientist in the energy space creating new technologies and driving innovation that promotes green energy and zero emission. He counts himself lucky to be on the path to creating a better world for posterity.

Rashish Adhikari is a graduate student pursuing an MS degree in Mechanical Engineering at the University of Texas at Tyler. After graduating with a bachelor's degree in mechanical engineering in 2018, he has been actively involved in designing and installing heating, ventilating and air conditioning (HVAC) systems. His passion and goals are in the field of green energy, HVAC, and green building design. Furthermore, he is also involved in social activities like fundraising for flood victims, sanitation activities, environmental and ecological awareness, motivational and career-building seminars, etc.

Diversity Statement

Diversity is a broad topic that shapes the lens we view our world regardless of whatever geographical location we may find ourselves. It emphasizes the differences we have based on background, race, sexual orientation, education, and socio-economic status, to mention a few. Because we acknowledge its obvious importance and reality, diversity is the core essence of our group, with four members comprising two Asian students and two Africans from 3rd world countries, who have been able to pool from our wealth of individual experiences to shape how we approached the project. For instance, each member of the group grew up in a 3rd world country where the incidence of high energy burden is an issue; often, many people in these countries are more comfortable trading off between efficient housing and basic amenities. Moreover, CO_2 emission is more pronounced in developing countries, and this is reinforced by a statistic from the Center for Global Development (CGD), where developing countries are responsible for 63% of current carbon emissions [1]. Hence, the motivation and the sense of value to contribute our quota to curb carbon in our targeted region of the USA through the jump into stem challenge. Apart from the inclusion of members whose race and background differ, it is also a widely held consensus that females are underrepresented in the stem field; as a result, women shy away from pursuing careers in stem-related disciplines or fields. This is buttressed by a non-profit organization-American Association of University Women-that females are massively outnumbered by their male counterparts in the science, technology, engineering, and math (STEM) fields, with women only making up only 28% of the STEM workforce [2]. Hence, in this project, without stereotyping the abilities of a female, we have ensured that a female is included and that her contributions, combined with others, are a driving force for the attainment of the project's set goals. Diversity is also accounted for through academic background. The different academic background of the individual member of the group-one chemical engineer and three mechanical engineers was leveraged during this challenge, especially each person contributing from their field of expertise to achieve a common goal- green energy and zero emission.

I. BACKGROUND

As global temperatures and population increase, it is expected that air-conditioning usage will proportionally increase especially in the world's hotter regions, which in turn will have a direct impact on energy consumption while driving up carbon emissions simultaneously [3]. Apart from the need to reduce carbon emissions of air conditioning (AC) systems, energy burden is an important topic in energy and cost savings. Among many factors that are pivotal in influencing high energy burden, energy-inefficient homes play a core role [4], and this may be due to older appliances or less efficient appliances in the home that needs upgrading. In the wake of a dwindling global economy, low-income households living in multifamily buildings and rented apartments within the area median income of or less than 80% and certain racial groups are at a disadvantage when it comes to the incidence of high energy burden because they pay more for energy per square foot than the average household- a clear indication of inefficient housing [5]. This underscores why policymakers and regulatory bodies such as General Services Administration (GSA) and EPA (Environmental Protection Agency) are implementing policies that will ensure overall building and energy efficiency [6].

II. PROBLEM STATEMENT

According to Comprehensive Housing Affordability Strategy (CHAS) data based on the 2015-2019 American Community Survey (ACS), 5-year estimate from the US Department of housing and urban development (HUD), it is estimated that 43 percent of Albuquerque households in New Mexico, which is one of the two prime cities considered in our proposed challenge, are in the three lowest income categories while 63.5% of all renter-occupied households and 29.3% of all owner-occupied households have incomes within the three lowest income categories [7]. Thus, forcing families to make trade-offs between energy consumption and other basic human necessities, such as medical care, clothing, and food. Energy consumption in these cities by the AC system accounts for 10.2% of total energy consumption in the US. The world at large is plagued with carbon emissions because of the increase in energy consumption. The mixed/hot-dry climate zone considered accounts for 846.6 lbs/MWh of CO_2 emissions per year [8]. This gives rise to a need to build a more energy-efficient AC system minimizing carbon emissions and reducing the trade-offs made by low-income communities.

III. SOLUTION

In existing air-conditioners (Figure 1(a)-1(b)), the condenser has coils with fins to cool the refrigerant. To increase the heat transfer through the condenser while reducing the compressor work, we proposed an evaporatively cooled condenser (Figure 1(a)-1(c)). Furthermore, the realization of a reduction in energy consumption will reduce the overall carbon emission from the system's operation.

Based on our proposed design concept for mixed/hot, dry climate (Albuquerque, New Mexico, and Las Vegas, Nevada) [9], we were able to reduce the compressor work on average by 24%, which accounts for a reduction of CO_2 emissions of about 4.5 billion lbs per year or 440 lbs per residential household per year.

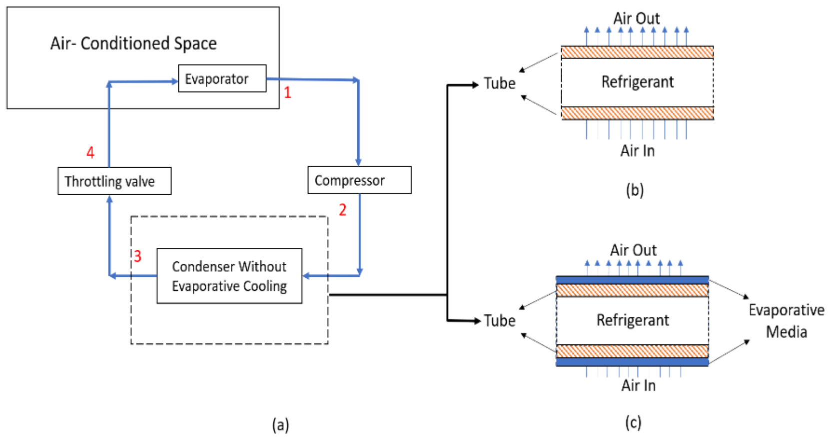

Figure 1. (a) Air conditioning system working cycle, (b) Condenser without evaporative media (standard design), (c) Condenser with evaporative media (proposed design)

Governing equations

The governing equations in the conventional and our proposed design complies with the first law of thermodynamics. Hence, the equations are based on the first law of thermodynamics.

The cooling capacity of the refrigerant or the refrigerant effect, $\dot{Q}_{ref}$, is given as:

$$\dot{Q}_{ref} = \dot{m}_{ref}(h_4 - h_1) \tag{1}$$

where,

$\dot{m}_{ref}$ is the mass flow rate of the refrigerant (lb/hr)

h_1 is the enthalpy at the inlet of the evaporator (Btu/lb)

h_4 is the enthalpy at the outlet of the evaporator (Btu/lb)

The compressor work, $\dot{W}_{compressor}$, is given as:

$$\dot{W}_{compressor} = \dot{m}_{ref}(h_2 - h_1) \tag{2}$$

where,

h_2 : *Enthalpy at the exit of the compressor (Btu/lb)*

The amount of heat released by the refrigerant in the condenser with and without the evaporative media is given by Equation (3a) and Equation (3b), respectively as:

$$\dot{Q}_{condenser} = \dot{m}_{ref}(h_2 - h_3) \tag{3a}$$

$$\dot{Q}_{condenser} = \dot{m}'_{ref}(h_2 - h'_3) \tag{3b}$$

where,

$\dot{m}'_{ref}$: *Mass flow rate of the refrigerant with evaporative media (lb/hr)*

h_3 : *Enthalpy at the exit of the condenser without the evaporative media (Btu/lb)*

$h_3{}'$: *Enthalpy at the exit of the condenser with the evaporative media (Btu/lb)*

For steady state condition, it is assumed that the water for the evaporative cooling process will be constant; therefore, the water gets evaporated, taking up the heat from the refrigerant flowing through the condenser, which can be realized with Equation (4) as below:

$$\dot{Q}_{condenser} = \dot{m}_w h_{fg}(T) \tag{4}$$

where,

$\dot{m}_w$: *Mass of the water evaporated into the air (lb/hr)*

$h_{fg}(T)$: *Latent heat of evaporation of the water at temperature T (Btu/lb$_w$)*
T : *Temperature of water fed into the evaporative media at our design condition (°F)*

The mass of the water evaporated into the air in Equation (4) can be related to the mass flow rate of the air into the condenser as:

$$\dot{m}_w = \dot{m}_a(w_0 - w_i) \tag{5}$$

where,
$\dot{m}_a$: *mass flow rate of air into the condenser (lb/hr)*
w_i : *specific humidity of the air at the inlet of the condenser (lb/lb dry air)*
w_o : *specific humidity of the air at the outlet of the condenser (lb/lb dry air)*

From the Equation (3b), (4), and (5), we get:

$$\dot{m}'_{ref}(h_2 - h_3') = \dot{m}_a(w_0 - w_i)h_{fg}(T) \tag{6}$$

Calculations

Among the refrigerants currently in use, R134a has one of the lowest Global Warming Potentials (GWP) [10]. Therefore, it is our preferred choice. The low-pressure range of R134a is (50-55) psi, and the high-pressure range is (250-275) psi. The pressure versus enthalpy diagram of the standard refrigeration system operating in the pressure range of $P_1 = 50\ psi$ and $P_2 = 250\ psi$ is shown in Figure A1 in the appendices. The values of the enthalpy at different states of the process are found to be:

$$h_1 = 109\ Btu/lb, h_2 = 124\ Btu/lb,\ h_3 = 61\ Btu/lb, h_4 = 61\ Btu/lb$$

According to the AC system buying guidelines offered by Carrier, an average AC system requirement for a normal household range from 1.5 tons to 5 tons [11]. Our proposed design assumes the AC systems capacity of 3 tons for further calculation. Hence, from Equation (1), the mass flow of refrigerant was found to be:

$$\dot{m}_{ref} = 747\ lb/hr$$

From Equation (2) and Equation (3a), the work done by the compressor and the heat lost by the refrigerant in the condenser was found to be:

$$\dot{W}_{compressor} = 11014\ Btu/hr,\ \dot{Q}_{condenser} = 47015\ Btu/hr$$

The properties of the air at our design locations were found to be as shown in Table 1.

Table 1. Properties of air at design condition [12]

Location	Outdoor air condenser inlet	Outdoor air condenser outlet
Albuquerque, New Mexico	$t_{ai} = 90°F, RH = 40\%$ $w_i = 0.0122\ lb/lb\ of\ da$	$t_{ao} = 107°F$ $w_o = 0.0158\ lb/lb\ of\ da$
Las Vegas, Nevada	$t_{ai} = 109°F, t_{ao,wb} = 67°F$ $w_i = 0.0046\ lb/lb\ of\ da$	$t_{ao} = 144°F$ $w_o = 0.0123\ lb/lb\ of\ da$

Assuming the temperature of the water fed into the evaporative media to be the average faucet temperature of our design location (Albuquerque, New Mexico, and Las Vegas, Nevada) 76°F [13] and $h_{fg}(76°\text{F}) = 1050.29\ Btu/lbm$. Keeping the value of the temperature of the water fed into the evaporative media constant and the mass flow rate of the air through the condenser constant with and without the evaporative media, the value of the temperature of the refrigerant at the exit of the condenser was varied to find the design level of cooling (3 tons) while reducing the mass flow of the refrigerant. The mass flow rate of air through the condenser and the mass flow rate of water into evaporative media are shown in Table 2.

Table 2. The mass flow rate of air through the condenser and mass flow rate of water fed into evaporative media.

Location (Design Conditions)	$\dot{m}_a (lb/hr)$	cfm of air	$\dot{m}_w\ (lbm/hr)$
Albuquerque	11001	2446	41
Las Vegas	5759	1280	45

From Equation (6), the reduced mass flow rate of the refrigerant of our proposed design system for both locations was calculated. The obtained mass flow rate of refrigerant resulted in a reduction in the work done by the compressor. The calculation results are shown in Table 2.

Table 3. Work done and saving in the compressor (Evaporatively cooled condenser)

Location (Design Conditions)	t_3' (°F)	h_3' $\left(\frac{Btu}{hr}\right)$	$\dot{m}_{ref}'$ $\left(\frac{Btu}{hr}\right)$	$\dot{W}_{compressor}$ $\left(\frac{Btu}{hr}\right)$	W_{saving} $\left(\frac{Btu}{hr}\right)$	Saving (%)
Albuquerque	40	27.1	441	6503	4511	41
Las Vegas	130	56.5	696	10262	752	7

The result in Table 3 shows, on average, about a 24% reduction in the compressor work at our design condition for the mixed hot/dry climate and hence CO_2 emissions to the atmosphere.

According to the 2015 residential energy consumption survey, the total energy consumption by the AC system is about 21.9 billion KWh per year [14] in our designed climate zone- mixed hot and dry. Out of which, our proposed design concept was found to reduce energy consumption by 5.26 billion kWh per year. The decrease in energy consumption can be related to the overall reduction of the carbon footprint. Both design conditions for our design concept are fed with the AZNM eGRID subregion. Furthermore, the average emission rates in the AZNM eGRID subregion to the national average emission of the CO_2[8], average emissions due to AC system without evaporative media (standard design) and with evaporative media (proposed design) are tabulated in Table 4.

Table 4. Relation of the emission of the gases with energy consumption

Gas	Emission	Standard Design	Proposed Design	Emission reduction	
	(lbs/MWh)	(Billion lbs)	(Billion lbs)	(Billion lbs)	%
CO_2	846.6	18.54	14.09	4.45	24

To conclude, the proposed design reduced CO_2 by 4.45 billion lbs per year, which is about 24% of the total emissions per year with the standard design.

IV. TECHNOLOGY-TO-MARKET PLAN

Economic Feasibility

To determine the economic feasibility of our proposed new concept in the evaporative cooling system, we carried out some calculations to determine the present value of future savings at discounted rates ranging from 3% to 10% [15] over a service life of 15 years with an average cost of electricity $0.15/kWh [16]. The present value of future savings represents the maximum additional cost for the implementation of the proposed modification to the coil of the condenser for the design conditions defined. The present value of the savings per year for a residential 3 tons of AC system with the proposed modified condenser is shown in Figure 2.

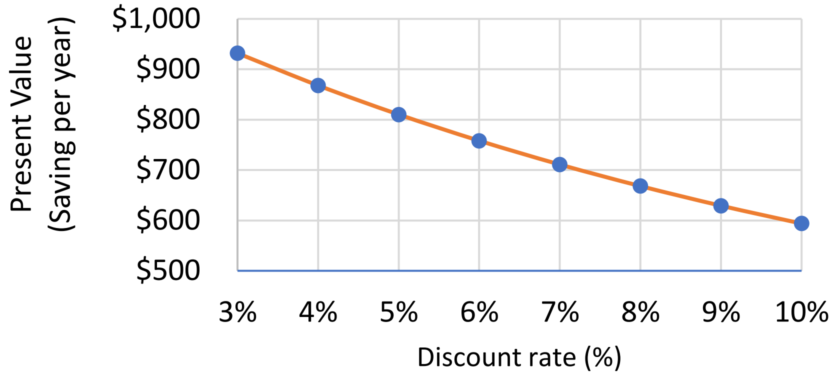

Figure 2. Present value of future savings per year with the varying discount rate (%) for 15 years

As mentioned earlier, Figure 2. shows the additional investment in implementing our proposed design concept. For instance, the maximum additional cost that can be incurred in the modification of the existing condenser system is about $600 at a discount rate of 10%.

Market Analysis

For our proposed concept, designing the prototype with a manufacturer is an important first step to bringing the solution to market. Our numerically validated concept will be presented to the Department of Energy; once it is certified as economically and technically feasible to contribute efficiently to the energy space or industry, an application for a provisional patent will be made to the United States Patent and Trademark Office (USPTO) [17]. Grants from appropriate bodies and notable agencies will be sought to build the prototype. One such notable agency is the Advanced Research Projects Agency-Energy (ARPA-E), reputed for sponsoring $3.27 billion in R&D funding for more than 1,415 potentially transformational energy technology projects [18]**.** Once the grant is secured and the prototype built, an application for a non-provisional patent will be filed. Subsequently, with the assistance of ARPA-E, the next important step is pitching our ideas to HVAC companies for the sole purpose of partnering with them to manufacture the product and bring it to market.

Aware of the market adoption barriers- behavioral, cost-effectiveness, product specifications, integration, and installation, amongst others that give incumbents advantages over potential entrants. Most consumers are concerned about the initial investment of HVAC technologies rather than looking at savings or performance in the long run- this could be some behavioral barrier that may inevitably affect the market acceptability of the product. For instance, the additional knowledge and information required for product installation and the non-energy factors that influence the adoption of the technology, such as noise level, comfort, brand reliability, size, and aesthetics of the equipment. These barriers can be overcome by our manufacturers, ensuring they feed and educate potential customers on the importance of energy-efficient appliances, which reduces energy burden as against just maintaining the status quo with existing technology. In addition, the manufacturability barrier is worth mentioning. These barriers are to determine whether it is feasible to modify an existing condenser or build a new condenser in its entirety with the evaporative media (proposed design concept). Moreover, our design product will involve feeding water into the media, and this comes with further analysis, such as the design and selection of pump, water source, and water distribution network, which will not be much of a barrier to product manufacturers given the availability of a wide range of pumps that is readily available in the market with the range of capacity.

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Appendix A

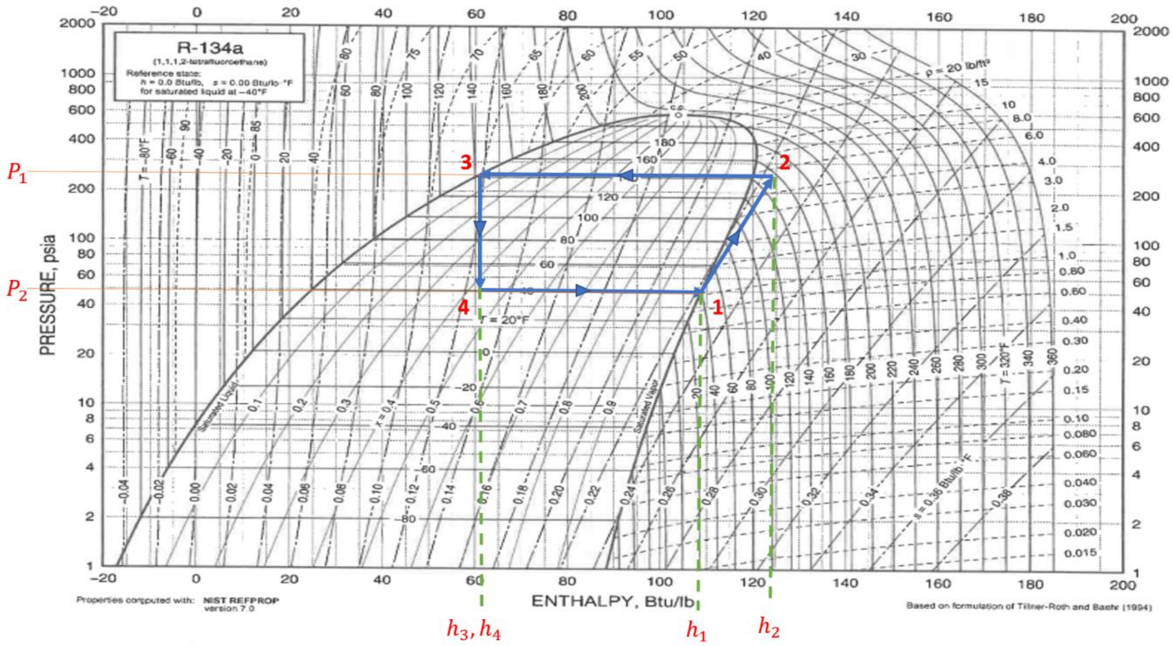

Figure A1. P-h plot of R134a operating between 50 psi and 250psi

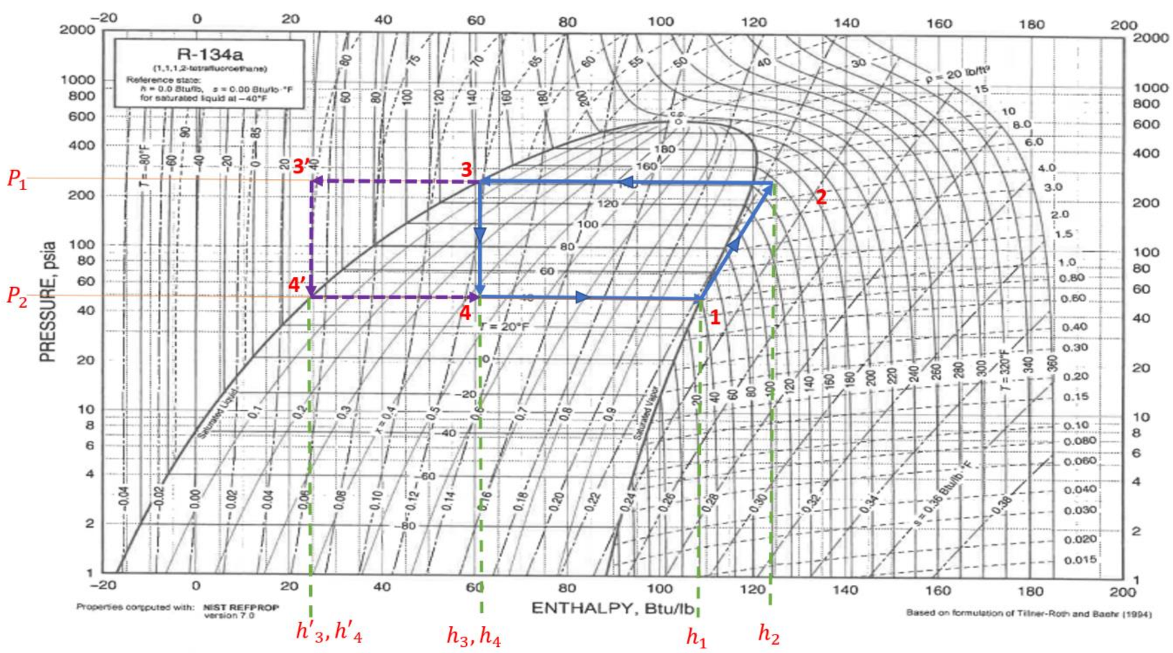

Figure A2. Figure A2. P-h plot of R134a operating between 50 psi and 250psi with evaporative media at Albuquerque, New Mexico

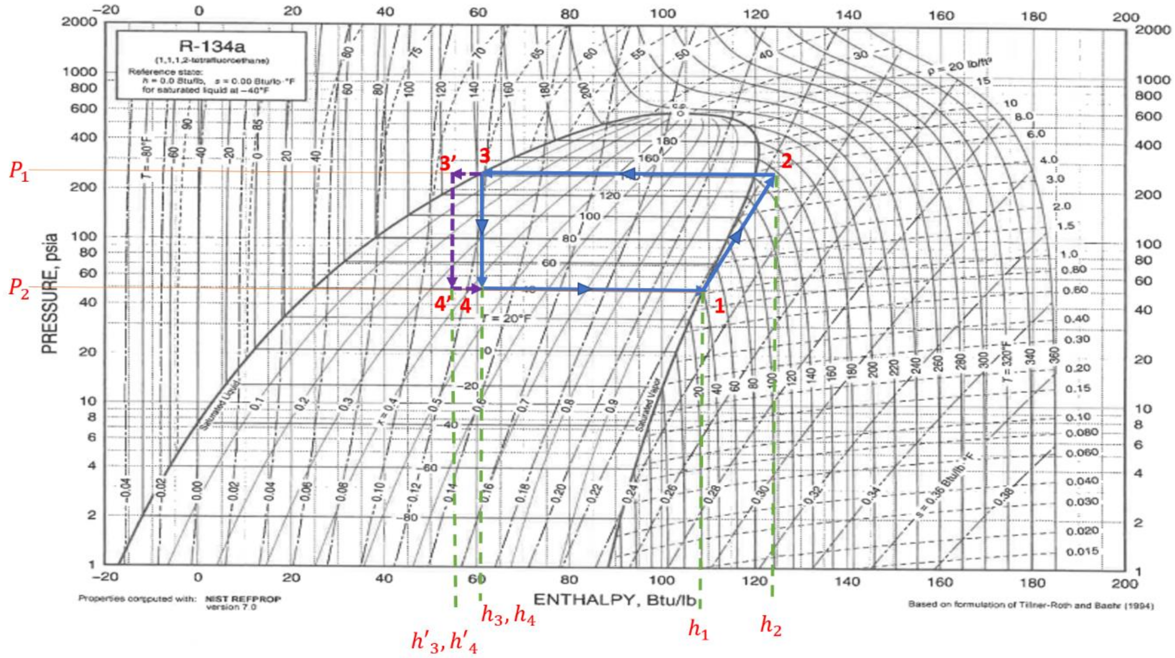

Figure A3. P-h plot of R134a operating between 50 psi and 250psi with evaporative media at Las Vegas, Nevada