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ENGM 311 Engineering Thermodynamics
George Fox University College of Engineering
Design Project

Team 7
Brady Pfeiffer, Ella Roberts, Gonzalo Rodriguez, Andrew Ross

Instructor
Bob Harder

ABSTRACT

This project report outlines the design of a refrigeration system for transportation of HIV and AIDS medication in Nigeria. Lack of access to refrigeration heavily impacts antiretroviral therapy efficacy and access in rural poor and slum dweller populations in Nigeria. Akwa Ibom, an epicenter of the HIV epidemic in southern Nigeria, has many hard-to-reach areas. In these areas, implementation of reliable and cost-effective refrigeration has the potential to improve treatment retention and quality of life for many. This report demonstrates, based on qualitative and quantitative factors, an optimal refrigeration system for this use case.

NOMENCLATURE

A_{cond}	Condenser area.	m^2
A_{evap}	Evaporator area.	m^2
COP	Coefficient of performance.	1
c_p	Water specific heat.	$\frac{kJ}{kg\ K}$
$Cost_{cond}$	Condenser cost.	USD
$Cost_{elec}$	Electricity cost.	$\frac{USD}{kWh}$
$Cost_{oper}$	Operating cost.	$\frac{USD}{kg}$
$Cost_{total}$	Total capital cost.	USD
ΔT_{lm}	Log mean T difference.	$°C$
h_j	Enthalpy at state j.	$\frac{kJ}{kg}$
L_w	Water latent heat of fusion.	$\frac{kJ}{kg}$
m_{ice}	Ice mass.	kg
$\dot{m}_{ice}$	Ice mass flow rate.	$\frac{kg}{s}$
$\dot{m}_{ref}$	Refrigerant mass flow rate.	$\frac{kg}{s}$
p_j	Pressure at state j.	kPa
$\dot{Q}_{ice}$	Ice heat transfer rate.	$\frac{kJ}{s}$
$\dot{Q}_{in}$	Heat transfer rate in.	$\frac{kJ}{s}$
$\dot{Q}_{out}$	Heat transfer rate out.	$\frac{kJ}{s}$
s_j	Entropy at state j.	$\frac{kJ}{kg\ K}$
t	Time.	s
T_{amb}	Ambient temperature.	$°C$
T_{high}	High operating temperature.	$°C$
T_j	Temperature at state j.	$°C$
T_{low}	Low operating temperature.	$°C$
T_{water}	Source water temperature.	$°C$
U_{cond}	Condenser heat transfer coefficient.	$\frac{W}{m^2\ °C}$
U_{evap}	Evaporator heat transfer coefficient.	$\frac{W}{m^2\ °C}$
$\dot{W}_{comp}$	Compressor work rate.	$\frac{kJ}{s}$
x_i	Quality at state i.	1
$\dot{\sigma}$	Entropy rate.	$\frac{kW}{K}$
σ_{gen}	Entropy generation.	$\frac{kJ}{kg\ K}$

INTRODUCTION AND BACKGROUND

In 2014, the UNAIDS program adopted fast-track targets to end the AIDS epidemic globally by 2030 [1]. The path toward meeting the UNAIDS target in Nigeria is limited by availability of reliable cooling. A 2018 report by Sustainable Energy for All recognizes Nigeria as one of nine countries with the biggest populations facing significant cooling-related risks. The report identifies "damaged or destroyed vaccines and medicines" as a telling factor of the magnitude of the cooling access challenge [2]. Rural poor and slum dweller populations lack the necessary resources to refrigerate antiretroviral therapy (ART) medication. Considering Nigeria's substantial number of impoverished rural and slum inhabitants, the provision of better cooling infrastructure would benefit its people living with HIV (PLHIV) [1].

Objective

This project report outlines the design of a refrigeration system to aid in the transportation of ART medication in Nigeria. The design intends to optimize a simple idealized refrigeration system for use in this case. The refrigeration system will produce 100 kg of ice every 12 hours, providing medication couriers with a central facility to access cooling. Optimization of the system considers capital costs of the design, operating costs from power usage, entropy generation, environmental impact, and social impact. Designing the optimal system involved analysis of different refrigerants and operating temperatures as well as consideration of qualitative criteria.

Location

The location of Nigeria is shown in Fig. 1. A 2022 analysis published for the Public Library of Science identifies two major epicenters for HIV infection in Nigeria, shown in Fig. 2. In Akwa Ibom, Fig. 3 in red, several local government areas (LGAs) report upwards of 8% HIV prevalence [3]. According to a study on community-based HIV control, Akwa Ibom has the highest HIV rate in Nigeria, but only 23% of its PLHIV are on ART. With diverse environments ranging from urban and metropolitan areas to agrarian and riverine communities to deep coastal regions, Akwa Ibom has numerous hard to reach areas [4]. Implementation of the refrigeration system outlined in this project report would allow couriers access to ice to keep ART medication stable on journeys to these areas.

Fig. 1. *Location of Nigeria*

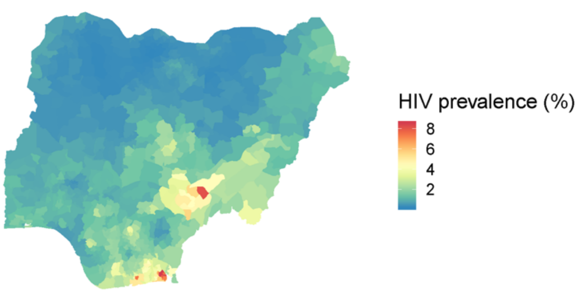

Fig. 2. *HIV Prevalence in Nigeria by LGA*

Fig. 3. *Location of Akwa Ibom in Red*

ANALYSIS AND MODEL

An ideal refrigeration system consisting of a compressor, condenser, throttling valve, and an evaporator was analyzed. Fig. 4 shows the layout of this system along with some assumptions made.

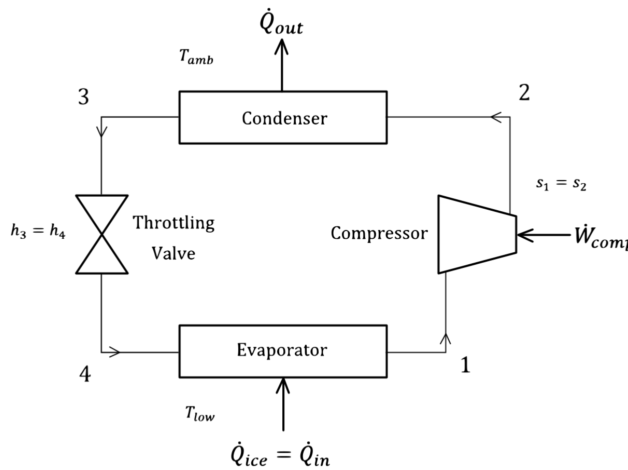

Fig. 4. *System Diagram and Assumptions*

<u>Ice-Evaporator Process:</u>

$$\dot{Q}_{ice} = \dot{m}_{ice}\left(c_p(0 - T_{low}) + L_w\right)$$

<u>Compressor Process (1-2):</u>

$$\dot{W}_{comp} = \dot{m}_{ref}(h_1 - h_2)$$

$$s_1 = s_2$$

<u>Condenser Process (2-3):</u>

$$\dot{Q}_{out} = \dot{m}_{ref}(h_3 - h_2)$$

$$\dot{Q}_{out} = U_{cond}A_{cond}\Delta T_{lm}$$

<u>Throttling Process (3-4):</u>

$$h_3 = h_4$$

<u>Evaporator Process (4-1):</u>

$$\dot{Q}_{in} = \dot{m}_{ref}(h_1 = h_4)$$

$$\dot{Q}_{in} = U_{evap}A_{evap}\Delta T$$

Analysis of this system was performed using F-Chart Software's Engineering Equation Solver. This allowed for testing of different conditions including operating temperatures and refrigerants. Choosing the best combination of these relied on careful thought of many factors. These factors included the following, in order of importance: benefit to PLHIV, social impact, capital cost, environmental impact, and coefficient of performance. We found benefit to PLHIV and social impact to be the most important factors to consider in designing our system. Prioritizing these in our design involved designing a system that would be accessible to communities in Akwa Ibom. For these reasons we only considered refrigerants accessible in Akwa Ibom. We compare these options in Table 1. We also aimed to minimize condenser and evaporator surface-areas when deciding temperature ranges, which would make these components easier to find and purchase. Temperature ranges are compared in Table 2. Additionally, these choices provide social value in the provision of jobs for locals, and opportunities for education about refrigeration.

Table 1. *Comparison of Refrigerants*

$Ref.$	COP	C_{oper}	C_{tot}	GWP
R22	3.09	0.002024	14123	1810
R134a	3.019	0.002072	12252	1430
R152a	3.174	0.001971	10405	124
R290	2.988	0.002093	14711	3
R600a	3.062	0.002043	13086	3

Table 2. *Comparison of Operating Temperatures*

T_{high}	T_{low}	σ_{gen}	C_{oper}	C_{tot}
30	-15	0.1751	0.001309	10897
30	-30	0.3378	0.001971	10405
35	-15	0.2205	0.001493	10888
35	-30	0.3937	0.002198	10623
40	-15	0.269	0.001691	11527
40	-30	0.4538	0.002443	11338

RESULTS AND DISCUSSION

Through our analysis and research, we concluded that R152a is the best choice of refrigerant for our system. R152a is a HFC alternative to some CFC and HCFC refrigerants, with an ozone depletion potential of zero and a low global warming potential of 124 [5]. The refrigerant is relatively cheap, and freely available, but it does carry some risks. Its flammability and moderate toxicity mean that special training and precaution would need to be taken when handling it. Out of the refrigerants tested in our analysis, R152a performed the best in many categories. Fig. 5 shows the p-h diagram of our proposed design with R152a.

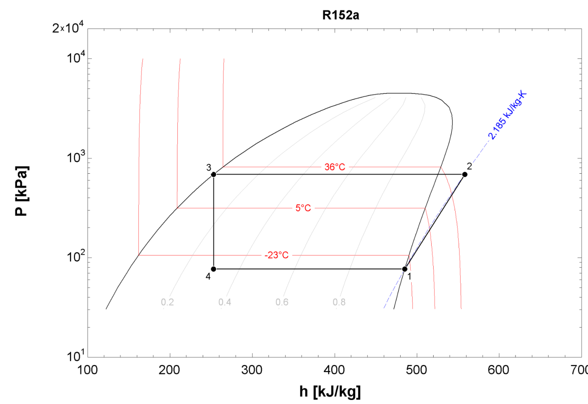

Fig. 5. *Pressure vs. Enthalpy Diagram of the System*

Operating temperatures that produced results consistent with our goals were at $T_{high} = 30°C$ and $T_{low} = -30°C$. This temperature range performed the best in its ability to reduce evaporator and condenser areas, reducing total capital cost to $10405. While this choice increased operating costs, yearly costs would only be $75, a trade off well worth the increase in an already very low number.

CONCLUSIONS

The refrigeration system designed in this project provides a cost-effective and reliable solution for transporting ART medication to PLHIV in Nigeria, particularly in hard-to-reach resource-constrained areas in Akwa Ibom. The optimized system design, which considers various factors, such as social impact and benefit to PLHIV, has the potential to improve the quality of life of many people living with HIV in Nigeria. The use of R152a as a refrigerant and the optimal temperature range of

$-30\ °C$ to $30\ °C$ not only reduces capital costs but also minimizes the environmental impact of the system. With special training and precaution, this refrigeration system has the potential to be implemented to relieve challenges in medication access and efficacy in Akwa Ibom.

APPENDIX

Entrepreneurial Minded Learning Reflections

Curiosity

Having a constant curiosity was immensely important in our work on this project. Consistently posing and communicating questions led us to learn valuable lessons. A key question we asked was: how can we optimize the system? A question we initially thought would be simple ended up being one of the most complex. We continued to find factors that played into this complex optimization. Through this, we learned that the optimal engineering answer often isn't the most practical solution. Quantitative analysis didn't paint the whole picture, disregarding factors like environmental and social concerns. Another question that came up was: why did we choose Nigeria as our country? Originally, we made the decision from two things. Nigeria was listed as a country with one of the highest cooling related risks and faces a substantial HIV epidemic. In our research to support this choice, we found a wealth of useful and meaningful information. This research also led to a connection we made with a researcher in Nigeria. A third important question we asked was: what implications and problems might arise from our system? Consideration of a thoughtful approach in analyzing the problem affected how we viewed hypothetical issues. Originally, we planned for the system to use R290, but considerations for the environment, safety, and social concerns led us to re-evaluate this choice. Through this re-evaluation, we found information about socio-economic issues permeating the epidemic, leading us to consider these issues more.

Connections

As our team worked on developing a final solution to address our project goals, we fostered meaningful connections between both ideas and people related to the subject of our project. A major connection we made was between the accessibility of cooling systems and equality issues. Nigeria's socio-economic inequalities translate to a lack of accessible cooling in rural poor communities. This means such places will often rely on infrastructure and organizations directed at providing temporary programs. This made the social impact of our system important in development. Another connection we made was between the importance of thermodynamics in combating the HIV epidemic, something we hadn't thought of before. Thermodynamic processes and principles determine the effectiveness of cooling for proper preservation of medication playing a critical role in control of the HIV epidemic. This connection helped us account for the importance of designing an ideal system as well as a practical system. An important connection we would not have made otherwise was through an email address provided in a study we found insightful [4]. We contacted Pius Nwaokoro, a researcher and healthcare provider in Nigeria to learn more about the HIV epidemic and gain additional knowledge from a person directly working on the epidemic. We were lucky enough to hear back and were able to ask Dr. Nwaokoro questions. In doing so, our team gained real insight into actual research being done in Akwa Ibom regarding ART implementation. We learned about the importance of community-based approaches to implementing HIV care, and that because ART regimens are so involved, making things easier for patients is key. We also unintentionally learned that it can be difficult to communicate over a large time difference.

Creating Value

This project taught us the importance of creating value. In implementing a refrigeration system like this, we would be able to provide value to Nigerians in resource constrained areas struggling with HIV/AIDS and access to safe medicine. This is a relatively inexpensive way to provide cooling and it would allow patients to have access to life sustaining medication. In addition, the creation of this system would provide value in creating jobs. Ranging from the manufactures of the system to the people delivering the medication in Nigeria, many jobs would be created. Implementation of a refrigeration system would require trained individuals to perform maintenance and repairs. This system could even open the possibility of relieving other cooling needs. Other types of medication, resources, and even food could be delivered. It also provides an educational opportunity for aspiring engineers and researchers to learn about refrigeration. A third valuable contribution from this system would be to investing stakeholders. Those funding the implementation of the system earn value in creating connections and trust with the communities they are assisting. Implementation of a system like this would require a hands on, community based approach. This develops a more altruistic relationship between those funding and the recipients of their support.

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