UNIVERSITI PUTRA MALAYSIA

SIMULATION ON THE PERFORMANCE OF A STIRLING COOLER FOR USE IN SOLAR POWERED REFRIGERATOR

KHALID OSMAN DAFFALLAH AHMED.

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2004
SIMULATION ON THE PERFORMANCE OF A STIRLING COOLER
FOR USE IN SOLAR POWERED REFRIGERATOR

By

KHALID OSMAN DAFFALLAH AHMED

Thesis Submitted to the School of Graduate Studies, Universiti Putra
Malaysia, in Fulfilment of the Requirements for the
Degree of Doctor of Philosophy

July 2004
To my parents, my wife, my daughter
and to all my brothers and sisters
Solar electricity produced by photovoltaic (PV) solar cells is one of the promising sources of power for solar refrigerator. Presently, solar PV is used to power conventional vapor compression or Rankine refrigerators. In this work, three photovoltaic freezers with different capacities and volumes of 100, 230 and 330 liters have been designed and tested. The freezers used the conventional vapor compression Rankine cycle. For the 100-liter freezer a minimum cabinet temperature of \(-20.1^\circ\text{C}\) was obtained. The maximum and minimum cooling capacity were semi-empirically computed to be 304W and 85.8W and the corresponding power consumptions were 139W and 70.1W respectively. Coefficient of performance was calculated to be 2.19 and 1.22 respectively at the maximum and minimum temperatures. For the 230-liter freezer, a temperature of \(-15.2^\circ\text{C}\) was achieved. The cooling capacity, power consumption, coefficients of performance were obtained semi-empirically. Similar experimental analysis was done on the 330-liter freezer to achieve a temperature of \(-5^\circ\text{C}\). All these freezers were tested for condenser temperature of 54°C and ambient temperature of 38°C.
Limitations of the vapor compression refrigerator were highlighted; these include insufficient power from the 75W solar panel to run the refrigerator’s compressor and therefore a backup battery is always required. But, battery is expensive and has a limited charge/discharge cycles.

To allow for the use of photovoltaic module to power bigger size refrigerator, a new age of refrigeration technology such as a free piston Stirling cooler is used to replace the vapor compression refrigerator. The free piston Stirling cooler uses small amount of power effectively besides elimination of battery since free piston Stirling cooler can use phase change material to store cooling when there is insufficient power (low solar insolation and night time operation).

The general principle in which a Stirling machine self-limits its operation was presented. The proposed design of the Stirling cooler was described and the performances of the cooler were simulated using the MATLAB computer software. Three types of analyses were carried out i.e. ideal adiabatic, Schmidt and non-ideal adiabatic.

Results from the ideal adiabatic analysis showed that the total power output was 101.2W. Coefficient of performance of 3.6 was obtained, which was found to be about 21.5% of the Carnot COP. The COP was calculated for cold space temperature of −10°C and warm space temperature of 27°C. The heat absorbed by the acceptor was found to be 44.28W while the heat released by the rejector was computed to be 56.51W.
For isothermal conditions of the working space and heat exchangers, Schmidt analysis was carried out for cold space temperature of \(-10^\circ\text{C}\) and warm space temperature of \(23^\circ\text{C}\). From the MATLAB results, work done on the expansion and by the compression spaces were found to be \(8.813\times10^{-1}\) and \(-9.283\times10^{-1}\) J respectively. Total work done was calculated to be \(1.145\times10^{-1}\) J.

The effects of the non-ideal heat exchangers and the difference in the working gas and wall temperatures were determined through a non-ideal adiabatic analysis. The gas temperature was obtained through iteration until convergence was achieved. Coefficient of performance of 3.8 was obtained for ideal regenerator and then reduced to 2.4 for a non-ideal regenerator when pumping loss was taken into account for the same temperatures of the working spaces.

Performance of operation, in terms of power consumption and cooling capacity, of the vapor compression refrigerator and Stirling type refrigerator was carried out. The comparison was based on the experimental data obtained for the vapor compression refrigerator and output data derived from MATLAB analysis for the Stirling refrigerator. The power consumption of the Stirling refrigerator was calculated to be 20 W while that of the vapor compression was computed to be 139 W.
SIMULASI KE ATAS PRESTASI PENDINGIN STIRLING UNTUK DIGUNAKAN DALAM PETI SEJUK BERKUASA SURIA

Oleh

KHALID OSMAN DAFFALLAH AHMED

Julai 2004

Pengerusi: Profesor Mohd Yusof Sulaiman, Ph.D.

Fakulti: Sains dan Pengajian Alam Sekitar

liter dan telah menghasilkan suhu pada -5°C. Semua penyejuk beku ini telah diuji untuk suhu kondenser pada 54°C dan suhu ambien pada 38°C.

Kelemahan peti sejuk jenis mampatan wap telah dinyatakan dan ini termasuk ketidakupayaan kuasa panel suria 75W untuk mengoperasi alat pemampat peti sejuk sehingga memerlukan penggunaan bateri penyokong pada sepanjang masa. Tetapi, penggunaan bateri adalah mahal malah bateri mempunyai kitar cas/nyahcas yang terhad.

Untuk membolehkan penggunaan modul fotovolta menguasai peti sejuk yang lebih besar, teknologi peti sejuk era baru seperti pendingin piston bebas Stirling lebih sesuai digunakan untuk menggantikan peti sejuk jenis mampatan wap. Pendingin piston bebas Stirling berupaya menggunakan dengan berkesan kuasa yang lebih kecil untuk membolehkan bateri diganti dengan bahan bolehubah fasa. Bahan seperti ini boleh digunakan untuk menyimpan tenaga penyejuk apabila kuasa elektrik berkurangan (dalam keadaan penyinaran suria yang rendah dan ketika malam hari).

Prinsip umum yang membolehkan mesin Stirling menghadkan operasinya juga telah diberikan. Cadangan rekabentuk pendingin Stirling telah diterangkan dan prestasi pendingin ini telah disimulasi dengan menggunakan perisian komputer MATLAB. Tiga jenis analisis telah dijalankan iaitu, analisis adiabatik unggul, analisis Schmidt dan analisis adiabatik tak unggul.
Hasil dari analisis adiabatik unggul memberikan jumlah kuasa bersamaan 101.2W. Pekali prestasi bersamaan 3.6 telah diperolehi, iaitu 21.5% daripada pekali prestasi Carnot. Pekali prestasi ini telah dikira untuk suhu ruang dingin pada –10°C dan suhu ruang hangat pada 27°C. Haba yang diserap oleh alat penyerap telah dikira dan didapati bersamaan 44.28W sementara haba yang dibebaskan oleh alat pengasing haba bersamaan 56.51W.

Untuk ruang kerja dan penukar haba jenis isoterma, analisis Schmidt telah dijalankan untuk suhu ruang dingin pada –10°C dan suhu ruang hangat pada 23°C. Hasil dari pengiraan MATLAB, kerja yang dilakukan oleh ruang pengembangan adalah bersamaan 8.813x10⁻¹J dan kerja yang dilakukan ke atas ruang pemampatan bersamaan –9.283x10⁻¹J. Jumlah kerja yang dilakukan telah juga dikira dan didapati bersamaan 1.145x10⁻¹J.

Analisis telah juga dilakukan dengan mengambilkira kesan dari penggunaan alat penukar haba yang tak unggul dan perbezaan suhu dinding gas dari ruang kerja. Suhu gas telah diperolehi dengan cara pelelaran sehingga hasil penumpuan diperolehi. Pekali prestasi bersamaan 3.8 telah diperolehi untuk alat penjana semula yang unggul dan nilai ini telah berkurangan kepada 2.4 apabila alat penjana semula tak unggul digunakan. Dalam alat penjana semula tak unggul berlaku kehilangan tekanan pada suhu ruang kerja yang sama.

Analisis prestasi operasi yang berkaitan dengan penggunaan kuasa dan keupayaan penyejuk bagi peti sejuk jenis mampatan wap dan Stirling telah dijalankan.
Perbandingan telah dibuat berasaskan kepada data eksperimen bagi peti sejuk jenis mampatan wap dan data yang diperolehi dari analisis MATLAB bagi peti sejuk jenis Stirling. Penggunaan kuasa bagi peti sejuk jenis Stirling telah dikira dan didapati bersamaan 20W sementara bagi peti sejuk jenis mampatan wap bersamaan 139W.
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I would like to express my sincerest thanks, gratitude and appreciation to Prof. Dr. Mohd Yusof Sulaiman chairman of my supervisory committee, for his invaluable guidance, helpful advice, suggestion, valuable support, endless patience and continuous encouragement throughout this project. His way of guiding, leading by doing is the best source of advice and is most effective.

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I certify that an Examination Committee met on 22nd of July 2004 to conduct the final examination of Khalid Osman Daffallah Ahmed on his Doctor of Philosophy thesis entitled "Simulation on the Performance of a Stirling Cooler for Use in Solar Powered Refrigerator" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

W. Mahmood Mat Yunus, Ph.D.
Professor
Faculty of Science and Environmental Studies
Universiti Putra Malaysia
(Chairman)

Zainal Abidin Talib, Ph.D.
Associate Professor
Faculty of Science and Environmental Studies
Universiti Putra Malaysia
(Member)

Zaidan Abdul Wahab, Ph.D.
Associate Professor
Faculty of Science and Environmental Studies
Universiti Putra Malaysia
(Member)

Noorddin Ibrahim, Ph.D.
Professor
Faculty of Science
Universiti Technology Malaysia
(Independent Examiner)

GULAM RUSUL RAHMAT ALI, Ph.D.
Professor/Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 26 AUG 2004
This thesis submitted to the Senate of Universiti Putra Malaysia has been accepted as fulfilment of the requirements for the degree of Doctor of Philosophy. The members of the Supervisory Committee are as follows:

Mohd Yusof Sulaiman, Ph.D.
Professor
Faculty of Science and Environmental Studies
Universiti Putra Malaysia
(Chairman)

Mahdi Abdul Wahab, Ph.D.
Faculty of Science and Environmental Studies
Universiti Putra Malaysia
(Member)

Azmi Zakaria, Ph.D.
Associate Professor
Faculty of Science and Environmental Studies
Universiti Putra Malaysia
(Member)

Zainal Abidin Sulaiman Ph.D
Associate Professor
Faculty of Science and Environmental Studies
Universiti Putra Malaysia
(Member)

AINI IDERIS, Ph.D.
Professor/Dean
School of Graduate Studies
Universiti Putra Malaysia
Date: 10 SEP 2004
DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

KHALID OSMAN DAFFALLAH

Date: 20.8.2004
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PV Photovoltaic
BLDCM Brushless DC Motor
P-h Pressure-enthalpy
COP, ε Coefficient Of Performance
Qₑ Heat absorbed by the evaporator
Qᶜ Heat rejected by the condenser
Wᶜ Work done to drive the compressor
Tₑ Temperature of the evaporator
Tₑₑ Temperature of the refrigerant in the evaporator
Tᶜ Temperature of the condenser
Tᶜᶜ Temperature of the refrigerant in the condenser
εᶜ Cartnot COP
ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers
Tₑ Expansion temperature
Tₑ Compression temperature
pV Pressure-volume
TS Temperature-entropy
cs Compression space
es expansion space
PV–TE Photovoltaic Thermoelectric