CR08-12

THE DEVELOPMENT OF A VUILLEUMIER CRYOCOOLER FOR NEW ZEALAND'S HIGH TEMPERATURE SUPERCONDUCTOR INDUSTRY

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ABSTRACT

A Vuilleumier cryocooler with a projected cooling capacity of 100 W at 77 K has been developed at the University of Canterbury in New Zealand. While most cryocoolers use mechanical compressors with associated vibration, leakage and lubrication problems, the Vuilleumier concept employs a thermal compressor with only a marginal mechanical work input requirement. This paper highlights its significant design advantages and presents results from a computer model that justifies this approach, despite the apparent disadvantage of the Carnot limitation arising twice.

INTRODUCTION

New Zealand has invested in high temperature superconductor technology (HTS) and is now in a significant position globally. Various local companies have already spun off this technology such as HTS-110 with laboratory magnets and Canterbury TX with transformers. It is anticipated that more companies will follow. The sheer number of possible applications of HTS technology necessitates the development of affordable, reliable and mobile cooling systems. This project originated from the need to provide an already existing and fast growing industry with a locally developed cooling system that can be specifically adapted and produced at lower cost.

1. BACKGROUND

1.1 Theoretical background

Any cold-producing devices such as Gifford-McMahon, Stirling or pulse-tube cryocoolers require a variation in the pressure of the working gas in order to achieve expansion and compression. This is usually done by a mechanical compressor in the form of a piston that reciprocates in a cylinder. However, a reliable seal design is required in order to avoid gas leakage past the piston and, unless precise and expensive clearance seals are employed, lubrication is involved. Lubrication, on the other hand, does not go well with machines that incorporate a regenerator such as Stirling and pulse-tube refrigerators as there is the risk of contaminating the fine pores of the regenerator matrix with the lubricant and thus significantly reduce the performance of those machines. Vibration and noise are further potential problems of mechanical compressors [1, 2, 3].

An even greater issue arises from the current demand of higher cooling capacities. The scaling-up of existing equipment to meet the required higher cooling capacities by simply increasing the physical size of these machines is often very difficult and typically disproportionately more expensive. One of the limiting factors in this exercise is the mechanical compressor that is usually driven by linear motors. It is common knowledge that the cost of linear motors increase disproportionately with their size and they become exorbitantly expensive. In addition to that, large mechanical compressors tend to be very noisy and heavy – quite often a decisive criterion in some cryocooler applications. A higher moving mass of a larger mechanical compressor also leads to more severe balancing issues.

A promising alternative is to use a thermal compressor that creates a pressure variation by a change in the temperature of the working gas instead of a change in volume as in a reciprocating piston machine. This principle is based on Rudolph Vuilleumier's invention from 1917 [4] and basically consists of a Stirling heat engine that is coupled to a Stirling refrigerator while sharing the same working gas. While it can be argued that a considerable disadvantage of using a heat engine as a compressor lies in the fact that the Carnot penalty has to be paid twice, significant design advantages may still justify the implementation of the Vuilleumier concept. This is the case even more so if a design is chosen that promises to be as nearly as efficient as a mechanically driven as will be shown below.

1.2 Working principle

A Vuilleumier refrigerator operates between three temperature levels – hot, ambient and cold. Its working principle can be best understood by first looking at how a mechanical compressor-type Stirling refrigerator works. Figure 1 shows a gamma-type Stirling configuration.

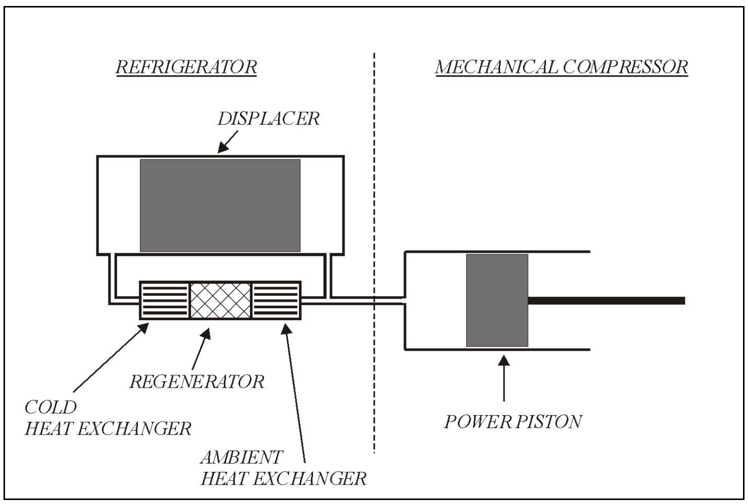

Figure 1: *Gamma-type Stirling refrigerator.*

A power piston reciprocates in a cylinder and creates a variation in pressure by changing the volume of the working gas. Separate, but connected to the compression and expansion cylinder by a port, is the refrigerator part. Here a displacer shifts the gas back and forth between two heat exchangers – a heat rejector at ambient temperature and the absorber at the cold end temperature. The motion of the displacer is out of phase by 90° with the power piston, such that the gas in the refrigerator is exposed to the cold end during the expansion phase and is exposed to the heat rejector during the compression phase. In between the two heat exchangers the regenerator is located, serving two main purposes: Firstly, it acts as a thermal barrier between the two temperature levels in order to avoid short-circuiting of thermal energy. Secondly, due to the porous structure of its matrix through which the working gas oscillates, the regenerator acts as a temporary heat store for the gas which picks up heat when moving away from the cold end and rejecting heat when moving away from the heat rejector heat exchanger. A Vuilleumier refrigerator has a similar working principle; however, the mechanical compressor on the right hand side is replaced by a heat engine while the remaining components in the refrigerator are identical (Figure 2).

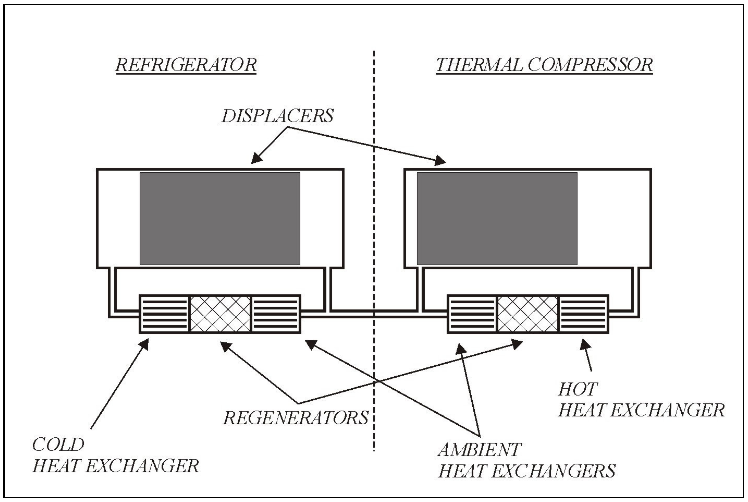

Figure 2: *Vuilleumier refrigerator.*

Here, the pressure variations are created by a change in temperature of the working gas. An additional displacer moves the gas between two heat exchangers and alternately exposes most of the gas to a hot temperature and to a cold temperature. Since the overall volume of the system remains constant at all times the gas pressure varies with the temperature according to the Equation of State. Again, compressor and refrigerator parts are connected via a port. Figure 3 shows a comparison between the Carnot Coefficients of Performance (COP) for a Vuilleumier machine and a Stirling refrigerator at given cold end temperatures. Ambient temperature is assumed to be 300 K whereas the hot temperature of the heat engine in the Vuilleumier configuration is 1000 K.

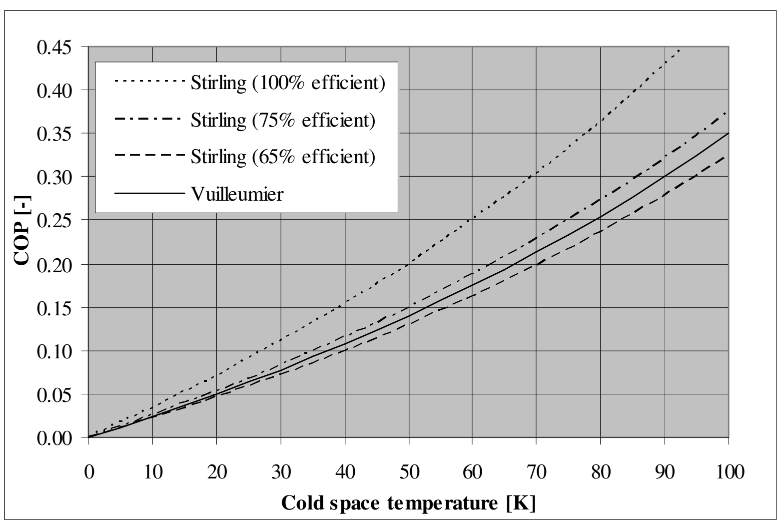

Figure 3: *Comparison of the Carnot-Coefficient of Performance (COP) for a Vuilleumier and a Stirling refrigerator with three different mechanical efficiencies.*

The diagram illustrates two things: the Carnot-COP of a Stirling is superior to a Vuilleumier where the Carnot efficiency of the thermal compressor has to be included as well, but the situation looks different if the efficiency of the Stirling's mechanical compressor is also taken into account. The diagram shows two efficiencies (75% and 65%) that straddle the COP-curve of the Vuilleumier and the assumed temperatures. The point to note is that mechanical compressors also have a limited efficiency and, as long as reasonably high temperatures are realised in the thermal compressor of a Vuilleumier machine, the COPs of both configurations are in the same range. However, there are significant design advantages for the Vuilleumier configuration as will be shown below.

2. DESIGN CONSIDERATIONS

The fact that the overall volume of the working gas remains constant in a Vuilleumier machine means that sliding seals which have to maintain a large pressure differential between the inside and the outside of the system can be abandoned. Instead, the gas envelope can be hermetically sealed by either static seals or, if practical, even be a fully welded enclosure.

A further advantage is the fact that no pistons are required to operate between a large pressure difference (and small ΔT). Instead it is possible to use displacers which do not have to compress the gas, rather, move it from one side to the other, only having to overcome gas friction (small Δp, large ΔT). This comparatively small work requirement means that smaller and cheaper linear motors are sufficient to drive the displacers. Since displacers have only a small pressure difference across them, seal problems are much less severe and the manufacturing tolerances are less tight which reduces the cost to a great extent.

The absence of problematic sliding seals and the ease with which the whole system can be sealed results in another advantage for thermal compressors: the average pressure of the working gas can be increased without the requirement for stronger mechanical compressors. Since the cooling performance is an almost linear function of the average system pressure, the machines can either be built smaller or, alternatively, the cycle frequency can be reduced. This last possibility is beneficial for the efficiency of the cycle as more time is available for heat transfer processes and fluid friction losses can be reduced.

Lubrication with all its associated issues can be avoided by the use of flexure bearings which are common practice in today's cryocooler technology. Flexure bearings are circular discs made of steel with slots in the form of a spiral. This allows the discs to flex normal to their faces while, at the same time, providing a high stiffness radially. A shaft that is supported by stacks of these discs is more or less centrally located and constrained, but is able to reciprocate along its axis. If the flexure bearings are designed such that occurring stresses remain well below the fatigue limit these components are not only maintenance-free but also exhibit a long lifetime.

Furthermore, the choice of flexure bearings and the need for displacers only instead of pistons facilitates the use of clearance seals. These are basically tight-fit displacers in cylinder liners that provide a gas seal through a very small clearance. Since displacers have to seal against a relatively small pressure difference across them, the machining tolerances are not as tight as in the case of pistons operating between a large pressure difference. This way of sealing makes redundant the use of sliding seals that are prone to wear and also eliminates the risk of seal material debris floating around in the gas cycle. Again, this contact-free gas seal in conjunction with lubricant-free flexure bearings are a very good match that promises reliability and longevity.

Using heat as the main energy input allows a high energy transfer rate per unit volume and per unit mass which is of particular importance for the demand of higher cooling capacities. Heat can be applied to the system without any noise or vibrations and the fact that different heat sources can be used depending on the requirements or the environment of the application may be an additional significant benefit. While, at first sight, it may seem irresponsible from a thermodynamic viewpoint to use electric heating, the situation looks different if the efficiency of mechanical compressors is taken into account (see diagram in Figure 3). Electric heating is very convenient and readily available and, after all, mechanical compressors also use electricity.

Thanks to recent design developments such as flexure bearings and linear motors, the Vuilleumier concept is now more attractive than it may have been several years ago. Also, advances in materials have pushed the boundaries in the use of light-weight components and high temperature insulation materials. Finally, and not least, a new territory has been opened up by digital electronic controls of linear motors. Instead of being constrained by a kinematic drive system, the position-versus-time relationships for the displacers can now be accommodated such that their motion follows more naturally the gas cycle in Stirling machines.

3. MODELLING

3.1 Background

For modelling of the gas cycle in a Vuilleumier cryocooler it is not necessary to represent the above mentioned design aspects in great detail. For the analysis and optimisation David Gedeon's Stirling simulation software package SAGE was used [5]. This allows the user to plug various modules together and connect them through relevant variables. For instance, the face of a piston is connected to the adjacent gas space through a volume variable. Or, a heat exchanger is linked to a connecting tube with a mass flow variable, whereas the heat exchanger wall is in thermal contact with a heat sink or source through a heat flow variable. All fundamental equations are solved for each module separately until the program converges to a final solution. SAGE has a mapping function which allows the specification of various parameters that are to be varied in given increments, as well as an optimisation function. All modules/components in SAGE may have two or more sub-levels where further input variables can be specified. For example, one sub-level of a heat exchanger could be the geometry of internal fins. Depending on how detailed the user wishes to model a system, SAGE takes heat conduction paths along solid and gaseous components into account, calculates fluid friction and pressure drops, and even shuttle and seal losses in piston/cylinder arrangements can be modelled.

Figure 4 shows how above mentioned Vuilleumier cryocooler configuration was modelled in SAGE. Both the refrigerator part in the lower half and the thermal compressor in the top half comprise the same components. Both double-acting displacers are neighboured by their adjacent gas spaces to the left and the right in the diagram, followed by connecting ports to the respective heat exchangers (upwards in the diagram). Both the refrigerator regenerator and the heat engine regenerator are sandwiched by the adjacent heat exchangers. The 'connecting duct' module at the far left at the bottom of the diagram connects the gas spaces of the refrigerator and the thermal compressor. Finally, the three temperature symbols at the bottom of the diagram represent the three temperature levels to which a number of heat flow variables are connected to.

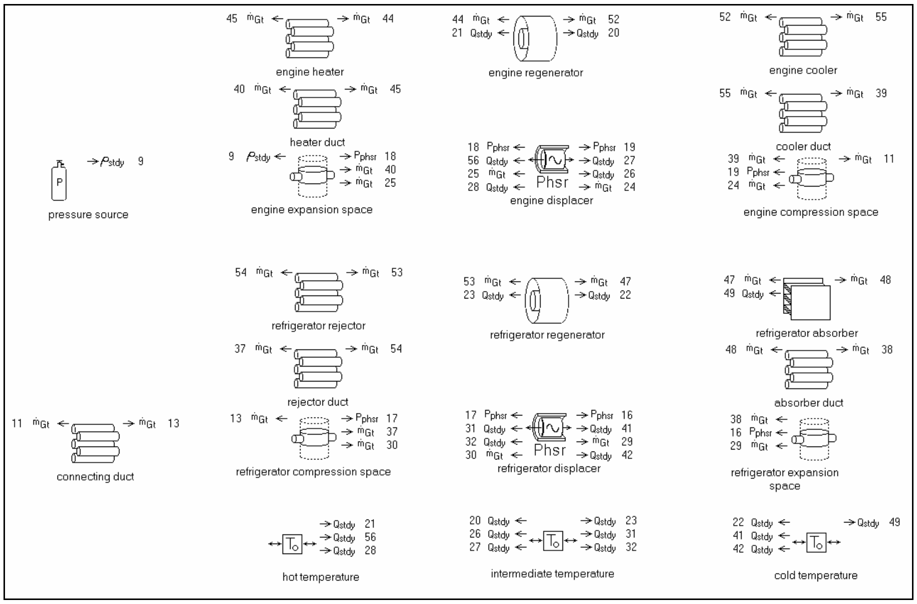

Figure 4: *SAGE-model of a Vuilleumier cryocooler configuration.*

3.2 Procedure of analysis

From the approximately 150 input variables 25 could be indentified as most critical. In order to find an optimum configuration, however, if one assumed a variation of each variable in three increments and a computing time of 10 seconds for each solution, it would take some 250,000 years to test all combinations. The dreaded search for the elusive needle in the haystack turned out to be relatively simple, though. It was found that if each component was optimised separately , one at a time, then repeated after all components had undergone this process, the optimum performance of the system had almost converged after one loop only.

The optimisation of each component was achieved through mapping by which typically three, four or five critical parameters were varied in up to ten increments each. SAGE records the user-specified output values for each combination which can then be displayed graphically in a spreadsheet. The optimum combination is easily found by sight, although a compromise between efficiency (COP) and cooling capacity had to be sought almost all the time.

Figure 5 shows a typical result of a mapping process for the regenerator. The achieved cooling capacity of the Vuilleumier cryocooler and its percentage of Carnot efficiency are plotted over the length of the regenerator for various outer housing diameters. For design constraints the inner diameter of the concentric tubular shape of the regenerator housing was held constant. Also the wire diameter and the porosity of the regenerator matrix were fixed after a material had been chosen. The arrows indicate the increase of the regenerator's outer diameter for both the cooling capacity plots and the Carnot-efficiency plots. Here it was relatively straight-forward to pick the smallest possible outside diameter of the regenerator since an increase in diameter had a detrimental effect on both the cooling capacity and the Carnot efficiency. The choice of the regenerator's length, however, was less clear as an increased length resulted in an ambiguous performance. A compromise had to be found where the Carnot efficiency was reasonably high at a still-acceptable cooling performance. Quite often the selection process was influenced by design considerations and/or constraints.

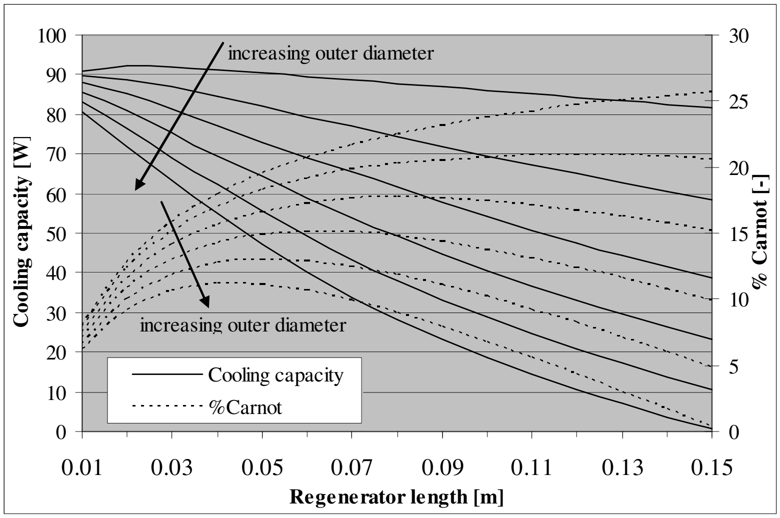

Figure 5: *Mapping result of regenerator analysis.*

4. ANALYTICAL RESULTS

Once all components were optimised and the performance of the chosen configuration could not be increased further, a performance chart could be plotted (Figure 6). This was obtained in varying the cold space temperature in the SAGE model and calculating the respective cooling capacity and Carnot efficiency. It can be seen that the cooling capacity is an almost linear function of the cold space temperature, with a value of somewhat more than 100 W at the design point of 77 K, reaching down to around 30 K with almost zero cooling capacity.

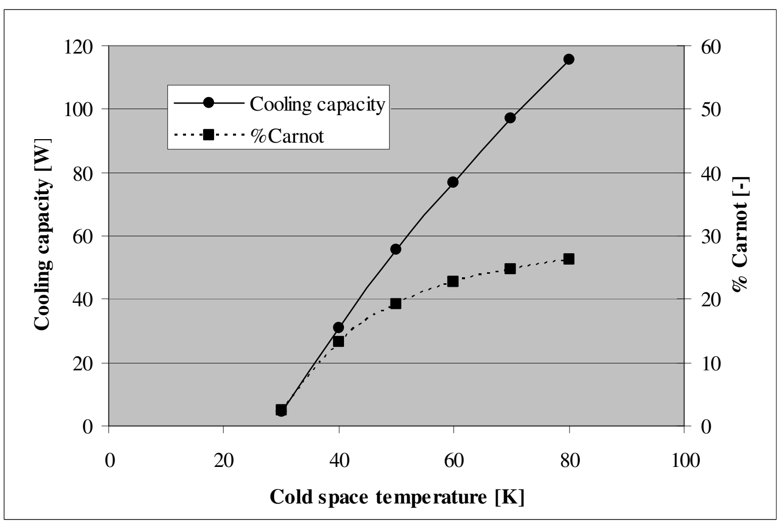

Figure 6: *Predicted performance chart of a Vuilleumier cryocooler configuration by SAGE.*

The predicted Carnot efficiency also drops with a decreasing cold space temperature but in a non-linear fashion. At the design point the Carnot efficiency of 25% is almost twice as high as commercially available pulse-tube or Gifford-McMahon cryocoolers with similar cooling capacities. It should be noted, however, that this is a computer model only that is partially based on ideal assumptions despite the fact that it takes a number of 'reality-effects' into account such as heat conduction paths, shuttle losses and irreversible heat transfer processes.

CONCLUSION

In view of an increasing demand of higher cooling capacities in today's cryocooler applications an alternative to mechanical compressor-type coolers is proposed. The use of thermal compressors as in Vuilleumier refrigerators offers a variety of design advantages which may result in quieter and more reliable operation, lower manufacturing cost and, as a computer model predicts, at least comparable efficiencies. The model predicts a cooling capacity of somewhat more than 100 W at a cold space temperature of 77 K and at a Carnot efficiency of 25%. The simulation results of the proposed Vuilleumier cryocooler configuration not only compare well with existing Stirling, Gifford-McMahon and pulse-tube cryocoolers, but also seem to justify the use of a thermal compressor as opposed to a mechanical one. While it should be noted that above presented results are only simulated and reality effects will take their toll, the outlook is very promising. The Stirling Group at Canterbury University has gained some confidence in SAGE's predictions from earlier modelling and subsequent experimental performance testing of non-cryogenic Stirling refrigerators [6, 7]. A prototype of the described Vuilleumier cryocooler is being manufactured at the University of Canterbury according to the results of the optimisation procedure with SAGE. Extensive testing is planned for the first half of 2008 with the implementation of smaller modifications in the second half of this year. Results will be published elsewhere.

REFERENCES

1. Walker, G., Cryocoolers, Part 1: Fundamentals, Plenum Press, New York and London (1983)
2. Walker, G., Cryocoolers, Part 2: Applications, Plenum Press, New York and London (1983)
3. Walker, G. and Bingham, E. R., Low-Capacity Cryogenic Refrigeration, Clarendon Press, Oxford (1994)
4. Vuilleumier, R., Method and Apparatus for Inducing Heat Changes, U.S. patent 1,275,507 (1918)
5. Gedeon Associates, 16922 South Canaan Road, Athens, OH 45701, U.S.A.
6. Haywood, D., Investigation of Stirling-type Heat-pump and Refrigerator Systems Using Air as the Refrigerant, Doctoral Thesis, University of Canterbury, Christchurch, New Zealand (2004)
7. Haywood, D., Raine, J. K., Gschwendtner M. A., Investigation of seal performance in a 4-a double-acting Stirling cycle heat-pump/refrigerator, Proceedings of the 10th International Stirling Engine Conference, Osnabrück, Germany (2001)

ACKNOWLEDGMENT

The New Zealand Foundation for Research, Science and Technology funded this project and contributed to its success in a manner which was very supportive but, at the same time, quite unbureaucratic.