Review of flow-through design in thermoacoustic refrigeration

Bammann T. C. , Howard C. Q. , Cazzolato B. S.

School of Mechanical Engineering, The University of Adelaide, Australia

ABSTRACT

The design and functionality of thermoacoustic refrigerators has been the focus of considerable attention from the research community since the 1980's. This environmentally friendly technology has the potential to become another option for refrigeration, as improvements in the design and technology are realised. Heat-exchangers are used to increase the efficiency of thermoacoustic systems, however they are typically complex to manufacture, expensive, and limitations of heat-exchangers exist in terms of efficiency and durability. Reducing or eliminating the use of heat-exchangers through the use of flow-through designs dramatically reduces the cost and complexity of thermoacoustic systems, potentially with minimal efficiency loss. In this review paper of flow-through thermoacoustic refrigeration, the developments of flow-through design and its potential benefits will be discussed.

INTRODUCTION

Thermoacoustics is a term used to describe the effect arising from sound waves creating a heat gradient, and vice versa. Thermoacoustic devices are typically characterised as either 'standing-wave' or 'travelling-wave' configurations, where the thermodynamic processes occur in a closed vessel. A full background and introduction to the subject of thermoacoustics is found in the textbook by Swift (2002).

An example of a standing-wave thermoacoustic refrigerator as a schematic, is shown in Figure 1, and in Figure 2 as a commercial application. An example of a travelling-wave thermoacoustic refrigerator is shown in Figure 3 as a schematic, and Figure 4 shows a commercial application. Figure 1 shows a thermoacoustic air-conditioner that comprises four heat-exchangers and two heat transfer devices that connect the heat exchangers. The cost of the heat-exchangers and heat transfer devices is a significant cost of the overall system. Thermoacoustic refrigerators are in general 20-30% less efficient than the equivalent vapour-compression systems (FAQ about Thermoacoustics, Penn State University). Flow-through design in thermoacoustics could be considered a relatively unexplored concept amongst the thermoacoustic community of 2005, and this will be discussed later in the article.

This paper will outline standing-wave and travelling-wave thermoacoustic refrigerator designs, and then review papers of the various open-cycle, or flow-through thermoacoustic refrigerator systems. A proposed concept from Swift (2002) will then be discussed to completely eliminate the use of heat-exchangers, followed by conclusions of this paper.

STANDING-WAVE REFRIGERATOR DESIGN

A design of a thermoacoustic standing-wave air-conditioner is shown in Figure 1. The design of this air-conditioner is similar to a conventional split-system, only the vapour-compression system has been replaced with a thermoacoustic system. The main components of the heat-pump are shown in the middle tube in Figure 1 and comprises a closed cylinder, an acoustic driver, a stack, and two heat-exchanger systems. The length of the closed cylinder is typically a half or quarter wavelength of the driving frequency. The vessel becomes resonant after the application of the acoustic driver,

and the pressure and particle velocity distributions are shown on the right hand side of Figure 1. The upper tube system in Figure 1 is used to dissipate heat from the thermoacoustic system to ambient air. The lower tube system is used to transfer heat from the indoor air to produce a cold air stream.
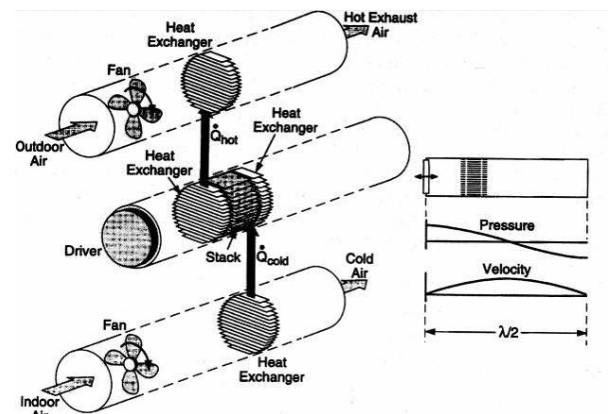

Figure 1. A typical half-wavelength standing-wave thermoacoustic refrigerator schematic (Swift, 2002 p. 191)

The heat-exchangers are used to improve the transfer of heat between the sub-systems. Although the plant shown in Figure 1 is an effective thermoacoustic system, the heat-exchanger sub-systems are typically expensive to manufacture; hence there is an opportunity to develop a cheaper alternative that does not require any heat-exchangers.

Reid et al. (2000) considers that a lower capital cost of a refrigeration system is often more important to industry than the efficiency, or its long term ongoing cost. Reid uses the example of the refrigeration process used in aircraft environmental control systems, where the weight saving justifies the low efficiency (10%).

An example of a standing-wave thermoacoustic refrigerator is shown in Figure 2, developed at Penn State University (Triton, 2005). The device provides 10kW of cooling power, and uses a double Helmholtz resonator design to increase the cooling capacity. The product has cooling output that is suitable for a small business or large home.
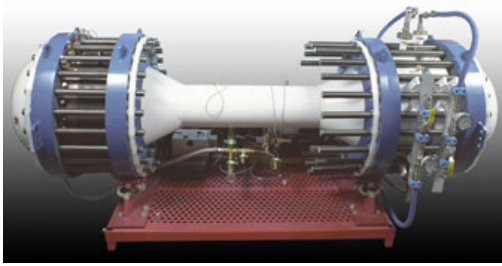
Figure 2. Standing-wave thermoacoustic refrigerator (Source: Triton: Shipboard Thermoacoustic Cooler, 2005)

TRAVELLING-WAVE REFRIGERATOR DESIGN

The travelling-wave system in Figure 3 (Swift, 2002) is a snapshot of a particular point in time, showing how the temperature distribution arises from the pressure distribution. The pressure is created with a moving piston, illustrated by the black rectangle on the left end. The impedance of the narrow tube and volume on the right is used to adjust the pressure amplitude and phase in the regenerator. Unlike the standing-wave system where pressure and position are in phase, the travelling-wave has oscillating pressure and oscillating velocity in phase.
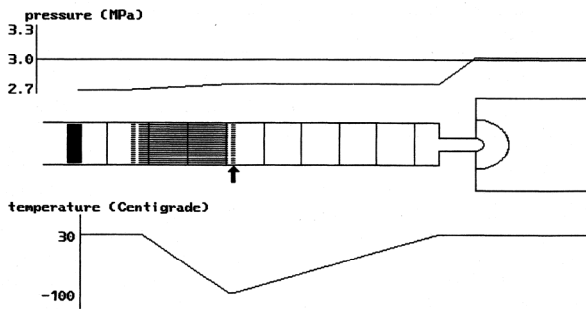

Figure 3. Travelling-wave thermoacoustic refrigerator schematic (Swift, 2002)

The travelling-wave system in Figure 3 uses a regenerator in place of a stack. A stack is designed to have intentionally imperfect thermal contact with the working fluid, whereas a regenerator is designed to have the greatest possible thermal contact with the working fluid.

A well publicised example (Sounds Cool! The Ben & Jerry's Project, 2005) of a travelling-wave thermoacoustic refrigerator used in a commercial application was an ice-cream cabinet, produced by the collaboration between Penn State University and Ben & Jerry's, shown in Figure 4.
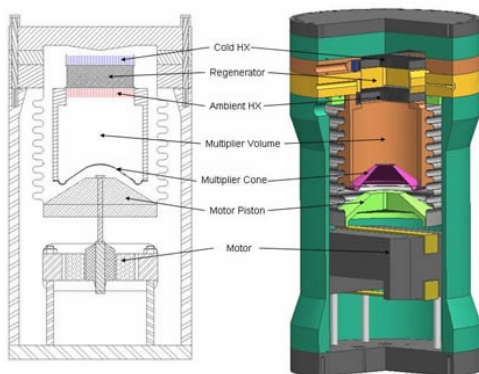

Figure 4. An ice cream cabinet powered by a travelling-wave thermoacoustic refrigerator (Source: Sounds Cool! The Ben & Jerry's Project, 2005)

The COP (coefficient of performance) for this device is measured to be 19% relative to the Carnot COP, for its given operating conditions.

FLOW-THROUGH STANDING-WAVE REFRIGERATOR DESIGN

Flow-through (or open-cycle) thermoacoustic systems have the characteristic that the working fluid moves through the system with a mean flow and an oscillating flow. The flow-through design enables the direct cooling of the working fluid, which is transferred out of the system via the mean flow, without the need for a heat transfer device that would otherwise be present. Flow-through design has the potential advantage of reducing manufacturing costs, since the mean flow makes the cold heat-exchanger heat transfer device redundant.

Swift (2002, p. 191) presents the concept flow-through of an air-conditioner shown in Figure 5, which is an adaptation of Figure 1. This concept utilises recirculation of the air to be cooled, as the thermoacoustic working fluid.
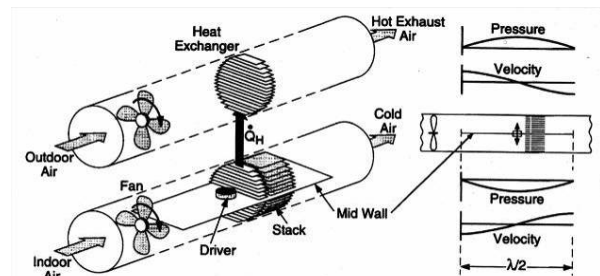

Figure 5. Flow-through design - utilising the air to be cooled as the thermoacoustic medium (Swift, 2002)

The driver of the half-wavelength resonator tube is now located at the mid-point, on a midwall, effectively creating two acoustic resonators. Swift (2002) suggests the drive frequency to be selected such that the midwall is half an acoustic wavelength of the two acoustic resonators, to prevent radiation of acoustic power downstream of the midwall.

Swift (2002) proposes two reasons that the system in Figure 5 can actually deliver a greater efficiency than that in Figure 1. Swift suggests that since the two heat-exchangers with associated losses are no longer implemented, there is potential for improved efficiency by eliminating a source of energy loss. Also, Swift's second explanation describes how Figure 5 is effectively a system which acts as many refrigerators in series, which effectively improves overall efficiency. This perspective is perhaps best summarised with the fact that the most heat is removed when there is a greater temperature difference between the hot and cold air streams, and recirculating the refrigerated air as the thermoacoustic medium achieves this greater temperature gradient.

Reid et al. (1998) present a schematic for a full wavelength thermoacoustic refrigerator. Reid's PhD thesis (1999) presents the schematic for a full wavelength toroidal thermoacoustic refrigerator in Figure 6, which is a significant enhancement of Reid et al. (1998). Reid et al. (1998) present results of stack temperature as a function of distance, with and without applied mean flow. Similarly, the rate of increase of total refrigeration power is calculated, as a function of applied flow.
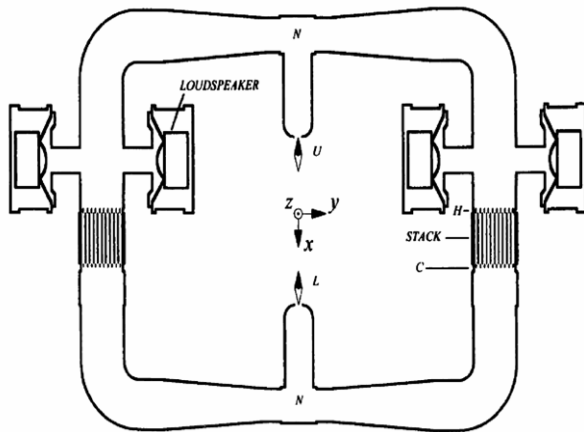
Figure 6. Schematic of a full wavelength toroidal thermoacoustic refrigerator, created as a demonstration device for open-cycle thermoacoustics (Reid, 1999)

The device was designed using four loudspeakers as shown, such that the two pressure nodes of the full wavelength standing-wave are located at the two points (Reid has) labelled as *N*. The hot and cold heat-exchangers are labelled as *H* and *C*. The cold heat-exchanger is not used for the device to function as a refrigerator. As a flow-through thermoacoustic refrigerator, the working fluid (air), which is also the gas to be cooled, enters through the top (labelled as *U*) and exits through the bottom (labelled as *L*). Alternatively, for the device to demonstrate its function as a heater, the cold heat-exchanger is used instead of the hot heat-exchanger, and the direction of flow is reversed. A photograph of the device is shown in Figure 7 (Swift, 2002).
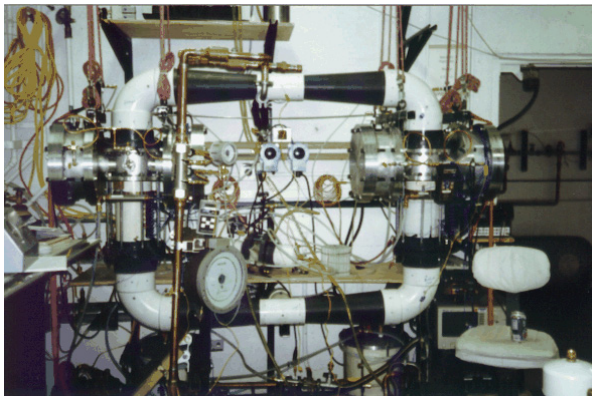

Figure 7. Flow-through standing-wave thermoacoustic refrigerator (Source: Swift, 2002)

The key experiment to Reid's thesis was the investigation of the effect of applied flow rate on the performance of the stack, and to see how this correlates with the numerical models he presents. Essentially, this was performed by maintaining constant resonator geometry, fluid properties (92% helium and 8% argon), constant temperature values of hot and cold heat-exchangers (hence constant temperature difference), and pressure amplitude (oscillatory pressure magnitude to mean pressure ratio) values. This was performed through adjusting water flow rate through the hot heat-exchanger, the loudspeaker power, and electric power delivered from the cold heat-exchanger to the stack.

For the system shown in Figure 6, Reid (1999) presents results of the 'temperature versus distance from the hot end at various applied volumetric flow rates' for both the left stack (p. 109) as shown in Figure 8, and also for the right stack (p. 106). For all intensive purposes, the results for both stacks are the same.
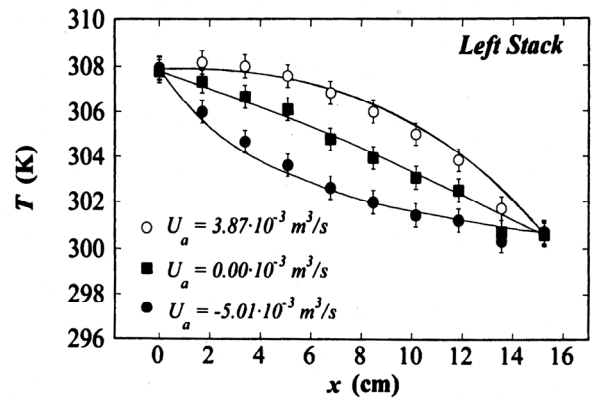

Figure 8. Temperature of the left stack (shown in Figure 6) versus distance from the hot end at various applied volumetric flow rates (Reid, 1999)

In Figure 8 the symbols represent different applied volumetric flow rates, where the positive rate is for creating a refrigeration effect, and the negative rate for creating a heating effect. The lines are produced using numerical results of Reid's theoretical model. Other results are presented by Reid (1999) are (for both stacks): 'Total refrigeration power versus applied volumetric flow rate', 'Performance indices versus dimensionless applied volumetric flow rate', 'Ratio of the open-cycle performance index to the closed cycle performance index, versus dimensionless applied volumetric flow rate' and 'Fractional Carnot efficiency (Second-Law effectiveness) versus dimensionless applied volumetric flow rate'. The measured 'total refrigeration power versus applied volumetric flow rate' closely correlates with Reid's numerical calculations, and any discrepancies are justified by hardware limitations and imperfections.

It is interesting to comprehend the *T-s* plot (temperature versus entropy) produced by Reid (1999, p. 52) in Figure 9, where the arrow indicates the movement of a fluid particle through the stack from the hot end to the cold end (as it would in an open-cycle thermoacoustic refrigerator). Each loop indicates an oscillation of the thermoacoustic cycle. These results are from theory developed by Reid (1999, p. 50).
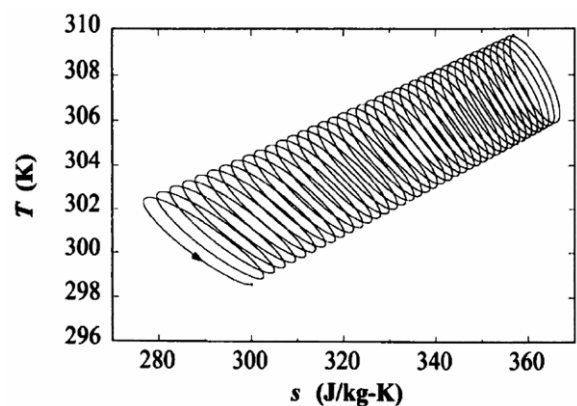

Figure 9. T-s representation of an inviscid open thermoacoustic refrigeration cycle (Reid, 1999)

In Reid's conclusion (1999, p. 129) it is stated:

"The superposition of applied flow on the thermoacoustic cycle was shown to enhance the First Law performance index for the device. However, the shape of the open thermoacoustic cycle in *T-s* space indicates its inherent irreversibility, as proposed."

Because of this, Reid (1999, p. 129) suggests it is:

> "… improbable that open thermoacoustic cycles will ever approach the efficiency of phase-change cycle technologies."

Reid (1999, p. 130) poses ideas for future work, such as better connecting the use of enthalpy flux ratios and performance indices described in his work, and extending the "inviscid-Lagrangian pathline calculation to consider viscosity". Reid has examined in detail the open-cycle thermoacoustic refrigerator, and it is mentioned in the conclusion that the engine and engine-heater "offer fertile ground for experimentation and development".

Reid et al. (2000) present a paper titled "Experiments with a flow-through thermoacoustic refrigerator", which in many ways summarises the work detailed in the PhD thesis of Reid (1999). The authors conclude that the result of the superimposed steady flow increases the COP by 20%, when defined as total cooling power against acoustic power. It is acknowledged that there are many design limitations with the demonstration device, and hence the 20% increase in COP does not truly reflect the full potential of superimposed steady flow. The paper concludes that it will be "interesting and important" to explore the details of the irreversibilities responsible for low percentages of COP relative to Carnot's COP, that they found for their refrigerator (as in Figure 6). The final remark of the paper:

> "... but we hope that engines, travelling-wave devices, and devices with perpendicular superimposed steady flow will also demonstrate interesting phenomena and lead to practical applications."

Hiller et al. (2000) demonstrate dehumidification of an air stream, through the use of a flow-through thermoacoustic refrigerator. The device used to perform the experiment was a modification of the device used by Reid et al. (1998). Two numerical models are utilised in this experiment, a 'fog' model and a 'wet-wall' model. The fog model assumes that the condensate is a homogenous tiny droplet formation, such that the droplets carry through the oscillating gas motion. The wet-wall model assumes that the condensate is on the stack walls, and that there is saturated water vapour between the stack walls, at the temperature of the stack wall. Figure 10 suggests that the wet-wall numerical model is far better than the fog model. Although it is acknowledged by Hiller et al. that the efficiency of their system is less than the efficiency of available vapour-compression dehumidification refrigeration technology, it certainly proves to be more reliable, and potentially cheaper to manufacture.
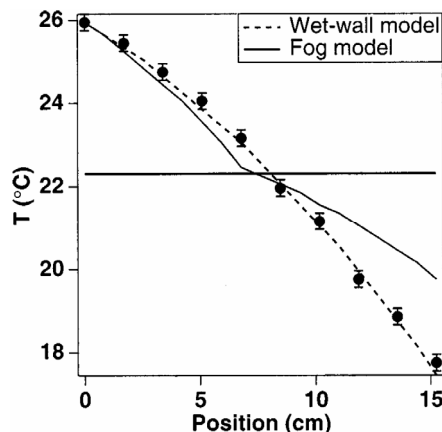

Figure 10. Experimental and numerical results of dehumidifying an air stream with a standing-wave thermoacoustic refrigerator demonstration device (Hiller et al., 2000)

It is interesting to consider an alternative to the elimination of the cold side heat-exchangers with flow-through design, and that is eliminating the use of a stack. Wakeland and Keolian (2002) have analysed the performance of thermoacoustic devices that utilise heat-exchangers without a stack. The conclusion of the paper was that such systems require a relatively large heat-exchanger surface area compared to systems that utilise a stack, and hence an unrealistically high heat transfer demand is placed on the heat-exchangers in this system. Another conclusion was that such systems do not offer any performance improvements in terms of efficiency, compared to systems that utilise a stack.

NO HEAT-EXCHANGER STANDING-WAVE DESIGN

Swift (2002, p. 195) introduces another concept in addition to the flow-through design, where he has also considered the addition of superimposed steady flow as a cross-flow, in Figure 11 below. The purpose for this concept is to eliminate the use of all heat-exchangers, thereby further reducing manufacturing costs of a thermoacoustic refrigerator.
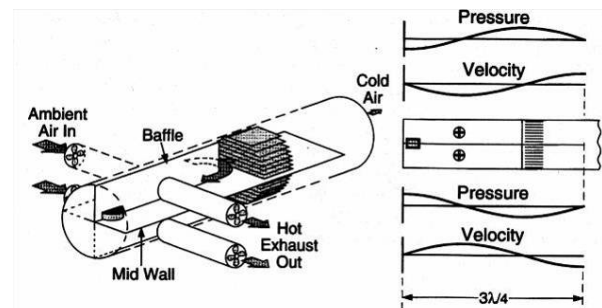

Figure 11. Thermoacoustic refrigerator showing elimination of all heat-exchangers through the use of cross-flow (Swift, 2002)

Figure 5 differs from Figure 11 due to the addition of the cross-flow (which is simply the 'Outdoor Air' from Figure 5), and the extra baffle to redirect this additional flow. The flow is drawn into the resonant cylinder with two streams, purely because of the midwall from Figure 5 dividing the resonant cylinder into two parallel streams. The ambient air is drawn into one side, and the baffle directs it into the stack. However, the exhaust streams on the opposing side of the resonant cylinder are simultaneously being drawn out, subsequently causing various air particles to switch direction inside the stack, and travel back down the opposite side of the resonant cylinder. In summary, the cross-flow stream is used to simultaneously transfer the waste heat from the stack into the atmosphere, whilst refrigerating the recirculated air.

It is worth mentioning in Figure 11 the midwall is different to that of Figure 5, in that it is now ¾ of a wavelength of the acoustic drive frequency, instead of ½ a wavelength. This is to ensure that the cross-flow streams and cool exit stream are positioned at pressure nodes, to minimise sound transmitted from the cold air duct.

The limitation with this concept is as the steady air stream is drawn out of the cylinder to harness the cold air stream, the hot exhaust air drawn out from the stack is to some extent forced to mix with the cool air. Potential limitations aside, Swift's cross-flow concept is worthy of further research, as the elimination of heat-exchangers will dramatically reduce the cost of manufacturing a thermoacoustic refrigerator for use as an air-conditioner. To quote Swift (2002, p. 195):

> "The quantitative understanding of oscillating thermodynamics in the presence of such a

perpendicular steady flow is a significant and exciting challenge."

CONCLUSION

This paper contains a review of flow-through designs of thermoacoustic refrigeration systems. Research in flow-through thermoacoustic refrigeration has shown that these systems can be as overall efficient as vapour compression cycle refrigeration technology, in many situations. Future investigation into cross-flow design is warranted for academic developments and may help encourage the use of thermoacoustic devices in industry.

REFERENCES

Hiller, R.A. & Swift G. (2000), *Condensation in a steady-flow thermoacoustic refrigerator*, Journal of the Acoustical Society of America 108(4), 1521-1527.

Sounds Cool! The Ben & Jerry's Project, Retrieved: 30 June, 2005, from Penn State University, http://www.acs.psu.edu/thermoacoustics/refrigeration/benandjerrys.htm

Frequently Asked Questions about Thermoacoustics, Retrieved: 9 September, 2005, from Penn State University, http://www.acs.psu.edu/users/sinclair/thermal/tafaq.html

Reid, R.S.; Ward, W. & Swift, G. (1998), *Cyclic thermodynamics with Open Flow*, Physical Review Letters 80(21), 4617-4620.

Reid, R.S. (1999), *Open Cyclic Thermoacoustics*, PhD thesis, Georgia Institute of Technology.

Reid, R.S. & Swift, G. (2000), *Experiments with a flow-through thermoacoustic refrigerator*, Journal of the Acoustical Society of America 108(6), 2835-2842.

Swift, G. (2002), *Thermoacoustics: A unifying perspective for some engines and refrigerators*, Acoustical Society of America.

Triton: Shipboard Thermoacoustic Cooler, Retrieved: 30 June, 2005, from http://www.acs.psu.edu/thermoacoustics/refrigeration/triton.htm

Wakeland, R. & Keolian, R. (2002), *Thermoacoustics with idealized heat-exchangers and no stack*, Journal of the Acoustical Society of America 111(6), 2654-2664.