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Towards the application of thermoacoustic cooling in office buildings: performance governing parameters and models for performance predictions

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Abstract

Solar assisted thermoacoustic cooling is with the recent advances in energy conversion efficiency an interesting alternative to sorption based technologies. Although thermoacoustic cooling is characterized with a slightly reduced COP, is has the advantage to require little to no maintenance and has zero global warming potential.

To successfully use the technology to cool office buildings an optimally designed machine and a careful building integration is required. To assess the integrated performance of building, thermoacoustic cooler and heat rejection system, the authors propose to use building and system performance simulation tools. However, there are no component models readily available to model a thermoacoustic cooler within those environments.

In this contribution the authors aim to determine the needed modelling complexity level for a component model of a thermoacoustic cooler. As the energy conversion efficiencies are sensitive to geometrical and operational parameter of the cooler the simplest models do not suffice.

As a result of a literature survey the authors suggest to use reduced high-order models of the cooler to assist design integration and performance prediction. The component model need to be able to account for the most important non-linearity's of high-amplitude acoustic waves.

Keywords – solar cooling, thermoacoustic engines, office building, energy conversion, renewable energy

1. Introduction

The changing climate and the increasing density of technical equipment in office buildings lead to an increasing demand of cooling to maintain a healthy and comfortable indoor environment. The number of options to provide cooling in building practice are limited and make traditionally use of technologies which convert high exergy electrical energy into low exergy thermal energy for cooling, such as compression chillers.

Technologies which make use of renewable energy sources such as absorption chillers powered by waste heat or solar energy are due to their technological complexity still not fully accepted [1]. An alternative concept for providing cooling based on solar energy is the application of thermo-acoustic engines combined with a thermoacoustic heat pumps.

Thermoacoustic engines are heat engines which convert heat into acoustic power which is subsequently converted into cooling power. The well accepted advantage of thermoacoustic engines is the simplicity of its mechanical buildup, characterized by no moving parts.

Another advantage is the instantaneous energy conversion providing cooling when the sun shines. Thermoacoustic cooling (TAC) is reported to have been successfully applied in space exploration and on naval vessels. However, limited knowledge is available with regards to its applicability for serving building conditioning systems.

The research questions to be answered by this contribution are:

1. Which models and modelling environments are available to predict the building integrated performance of thermoacoustic coolers?
2. Which modelling abstraction level is required to satisfactory represent the system performance for conceptual building and system design?

2. Methodology

To answer the research questions three methods are applied: (1) literature and software survey; (2) performance evaluation of an building integrated thermoacoustic cooler.

3. Solar assisted cooling

The research interest into solar-thermal cooling technologies is motivated by two observations: (1) the increasing demand for air conditioning has led to an significant increase of the peak electricity demand, and (2) the refrigerants used in traditional vapor compression technologies contribute severely to the global warming [1, 2].

However, although solar-thermal cooling technologies are being considered important to reduce CO_2 emissions only sorption based technologies are being considered technologically mature. Technologies based on steam jet cycles or cycles which convert heat to mechanical energy and mechanical energy to coolth, such as TAC, are considered less significant.

Table 1 gives an overview of important characteristics for three solar assisted cooling technologies: solar-electric vapor compression, solar-thermal absorption and solar-thermal thermoacoustics. It can be noticed that TAC is characterized by COP`s comparable to absorption chillers whilst having a global warming potential of zero and needing no or little maintenance.

Table 1. Solar cooling technologies - overview

	Compression chiller	Absorption chiller	Thermoacoustic chiller
References	[3, 4]	[3, 5, 6]	[7-9]
Conversion steps	thermal-phase change-phase-change - thermal	thermal-chemical; chemical-thermal	thermal-mechanical, mechanical-thermal
Cooling capacity	3.5 – 7000 kW	200 – 6000 kW	4 – 120 kW
Refrigerant	Hydrofluorocarbons (HFC`s)	H_2O-Libr/ H_2O-NH_3	Argon
Global warming potential refrigerant	high	low	none
Energy source	solar-electric	solar-thermal, residual heat	solar-thermal, residual heat
Efficiency (COP)	3.5-6	0.6-1.2	0.55-0.7
Range of operating temperatures	Small (limited by phase change)	Small (limited by phase change	Large(no phase change)
Maintenance	regularly	regularly	none - little

The pre-conditions for solar-thermal cooling to be successfully integrated into the building services concept are threefold:

1. Location: The location is characterized with high availability of solar energy.
2. Building energy demand: There is a significant demand for either heating, cooling and/or domestic hot water.

3. Coincidence of solar gains and energy demand: The demand characteristics of the building coincide to a large degree with solar energy availability, thereby reducing the need for thermal storage.

Furthermore, there are a number of shortcomings reported from experiences with absorption chillers in practice, which also apply to TAC, that need to be carefully considered. Shortcomings have been reported in the area of design integration and energy management as well as high maintenance efforts due to an increased system complexity [1].

Particularly, the additional hydraulic network needed for the required heat rejection as well as the part load performance of the cooling towers present a challenge to be addressed.

However, the identified advantages of thermoacoustic cooling technologies make it worthwhile to investigate their potential to provide space cooling. To investigate and overcome the challenges associated with the integration of solar-thermal cooling technologies to a building design, building and system simulation techniques represent a cost effective option.

Building & System modelling and performance simulation

One possibility to address those design challenges is the adoption of building and system performance simulation. The application of building and system simulation enables the design team to quantify the integrated system performance relatively, in response to changing the system design or to variation of design parameters or absolutely, in case a calibrated system model is available.

An precondition for using building and system simulation is the availability of component models. Whilst the selection of integrated building performance simulation tools is extensive, see [10]. Only a number of tools provide the capability to model and integrate the buildings and complex hydraulic systems. A tool review indicated the availability of a great variety of solar thermal collector and heat pump component models but no component model which represents a two-stage thermoacoustic cooler.

System components can be modelled with different degrees of complexity. The degree of complexity to be chosen depends on the level of accuracy required at the design stage. It is well accepted that the expense for modelling increases with increasing modelling complexity. Energy conversion technologies, as the TAC, can be modelled with at least three different levels of complexity: low, medium and high complexity:

1. Low complexity, the TAC is represented with a rigidly defined averaged coefficient of performance.

2. Medium complexity, the coefficient of performance varies in response to variations in external boundary conditions such as cloud cover, ambient temperature and building cooling load.
3. High complexity, the coefficient of performance is a derivative of the first principle physics of the underlying energy conversion processes including localized energy losses and non-linear effects.

For consistency low and medium complexity models are from here on referred to as low-order models whilst high complexity models are for the remaining part of the contribution referred to as high-order models.

THEAC25 an TFF research project

Simulation models provide reliable information only if they have been calibrated using reliable techniques and data [11]. In order to arrive at reliable measurement data a two stage thermoacoustic cooler is currently being assembled in the Sustainable Energy Systems Lab at the Saxion University of Applied Science. The aim is to evaluate its dynamic performance under close to real conditions.

Fig. 1 Energy conversion diagram for 24kW cooling capacity

The objective of the Technology For Future (TFF) project is to scale-up an existing two-stage 1.5 kW prototype [12] to provide a cooling capacity of 24 kW. A schematic of the energy conversion steps is indicated in Fig. 1. The project provides the opportunity to investigate dynamic performance efficiency, design integration and energy management.

4. Thermoacoustic engines

Thermoacoustic engines are differentiated into two types: standing wave and traveling wave engines. Whilst standing wave engines make us of a stack, traveling engines use a regenerator to generate an acoustic wave from a given temperature difference. Both types make use of the "timing" between the periodic pressure amplitude and gas displacement in an acoustic wave to force the gas to undergo a thermodynamic cycle.

An acoustic wave is characterized by pressure variations. The pressure variations result in an oscillating motion of the energy transfer medium. In essence, thermoacoustic engines make use of the mediums temperature and position variation which represents an reversible motion of the medium to transfer energy. In open air pressure amplitude , gas displacement and temperature variations in an acoustic wave are very small

For example, a spoken word at 65 dB generates a pressure variation of 0.035 Pa and a gas displacement of ca. 0.6 micro meter. The resulting temperature variation is approx. 40 micro Kelvin.

Inside a thermoacoustic engine the typical sound pressure level could reach 180 dB which creates a pressure variation of 30 kPA, a gas displacement of 10 cm and a subsequent temperature variation of 24 K.

It should be noted that these amplitudes occur only inside the pressurized and closed system of the TAC. Due to the reaction force of the oscillating gas column inside the TAC some external vibration can be observed but the acoustic noise in general is less than the noise of the circulation pumps.

Solar thermal thermoacoustic cooling

Solar driven thermoacoustic coolers are composed of two main components, the thermoacoustic engine and a thermoacoustic heat pump sharing the same acoustic resonance and feedback circuit.

The engine, consisting of two heat exchangers (HX) separated by an regenerator, converts the (renewable) solar thermal energy into acoustic power (mechanical energy) in the form of an powerful acoustic wave. The acoustic wave is generated from the temperature difference across the regenerator. Whilst the hot HX of the regenerator is fed by the solar heated fluid, the cold HX is maintained at a lower temperature, close to the ambient temperature. The thermodynamic process occurring within the regenerator can be described by a reversible Stirling cycle.

The acoustic wave or pressure variation are created by the oscillating movement of the gas parcels within the regenerator between the hot and cold heat exchangers. The back and forth movement can be described as follows. The gas parcels volume expands nearly isothermally at the hot HX, passes isovolumetrically through the regenerator, cooling down. At the cold HX the gas parcel undergoes isothermal compression and heats up again with constant volume on its path back through the regenerator to the hot HX.

The heat pump`s built-up is the same as the thermoacoustic engine`s but its functionality is different. Instead of using a temperature difference to generate an acoustic wave, the acoustic wave generated by the engine is used to generate a temperature difference between two heat exchangers of which one is kept at a temperature close to the ambient temperature. Dependent of which HX is used as hot HX relative to the direction of the acoustic wave its mechanical energy can be used to cool or heat the medium used to power the second HX.

Performance efficiency

The parameter governing the energy transfer between the heat engine and the heat pump is the acoustic power. To increase the acoustic power (gain) thermoacoustic engines s can be connected in series, creating multiple stages.

Travelling wave thermoacoustic engines are reported to show efficiencies up to 50% of the Carnot efficiency. The improvements, in comparison to standing wave engines, are reported to be the result of avoiding a number of non-linear effects caused by high-amplitude waves. Non-linearity's can result in flow phenomena such as vortexes which lead for example to acoustic streaming, one of the most important non-linear effects. Acoustic streaming is describes by Scalo et al. [13] as:

"... the cumulative effect of fluid parcel displacement over several high-amplitude acoustic cycles. The result is a rectified flow that when unsteady, may evolve over time scales orders of magnitude larger than the fundamental acoustic frequency."

Scalo et al. argue that the performance efficiency of thermoacoustic energy converters cannot be accurately modelled with low-order models as they are not able to capture the non-linear effects. Due to the failure of low-order models, higher-order models are being developed to allow the optimization of heat engines by identifying efficiency enhancing measures.

The intensity of research in the field shows that it is expected that the maximum conversion efficiency that is currently achieved can be further enhanced. The performance governing parameters can be differentiated into two group geometry and operations related parameters. A not conclusive number of parameters is exemplary listed in Table 2.

Table 2. Performance governing parameter for heat engines, example

Operations related parameter	Geometry related parameter
Charge pressure	Resonator length
Onset temperature difference	
Resonance frequency	
Pressure amplitude	

Modelling and simulation of Thermoacoustic engines

First results from the literature survey indicate a great variety of modeling approaches being applied to model thermos-acoustic heat engines. The modelling approaches range from electric resistance analogy models based on fixed performance efficiencies, over models which numerically integrate one-dimensional wave equations to full three-dimensional computational fluid dynamics models.

Low-order models

The paragraphs below briefly introduce three different modelling approaches on the example of three different modelling environments. The low-order models are refereed being used as design tools for steady state design calculations being able to deal with low-amplitude acoustic waves.

Sage is a commercial modelling simulation and optimization environment for Stirling cycle engines and coolers written in DELPHI. It has been developed to determine the performance of pulse-tube coolers and cryocoolers in response to a number of design parameters [14]. System models are assembled from a number of available component objects, which are based on simplified gas flow and heat transfer physics. Model descriptions of a thermoacoustic engine, a Sondhauss Tube are available indicating its ability to model simple heat engines [15]. The embedded optimization functions makes use of an adapted version of Powell's sequential-quadratic-programming method.

DeltaEC is probably the most acknowledged tool in the domain of thermoacoustics. It is non-commercial design environment for Low-Amplitude Thermo Acoustic Energy Conversion to be used for performance predictions and design calculations of thermoacoustic equipment. The core has been coded in FORTRAN-77 and the interface is built on Python. The calculation kernel is designed to integrate one dimensional wave and energy equations in gas filled volumes such as ducts, stacks and regenerators assuming time dependence. The resulting wave equation resembles a second-order Helmholtz differential equation for pressure amplitude. The objects are being connected by the user For each of the object the differential equations are integrated and variables matches at the connections between segments [16].

High-order models

As stated before high-order models are used to analyze high-amplitude acoustic waves in steady or transient state. Those complex models are able to reproduce the non-linearity's of the gas flow. Furthermore, they are able to directly account for the interaction of high-amplitude waves and complex geometries, transitional turbulence and/or the effect of higher order harmonics on the thermoacoustic energy transport.

Models that are reported to be used are fully fledged general puropose CFD codes such as CFX [8, 17].

Tina^{TM}

An alternative approach is the application of the electric analogue. Riley reports in [18] the successful use of an electrical network solver, called Tina^{TM} predict the qualitatively transient behavior of a thermoacoustic engine under steady state as well as transient conditions. Tina^{TM} is a SPICE based commercial analysis environment. SPICE stands for simulation program with integrated circuit emphasis. Riley claims to be able to reproduce non-linear phenomena such as squegging and harmonics.

5. Summary

The comparison of solar assisted cooling technologies indicates that thermoacoustic cooling is an feasible alternative to absorption cooling.

Thermoacoustic cooling is characterized with a slightly reduced COP compared to sorption based technologies but has the advantage to require little to no maintenance and has a zero. global warming potential.

However, there are a at least two challenges associated with TAC: (1) the design and management of the required heat rejection system and (2) optimization of the TAC performance to achieve the projected COP in operation. The first is in two areas: design for maximum energy efficiency and building integration.

Three different modelling approaches could be identified to analyze the machines performance response to the external ambient conditions and the buildings cooling demand, fixed COP, variable COP, use of first principle models. The literature review indicated that there are no high-order models available which support building designers to integrate a thermoacoustic cooler to a given building design. However, designer can easily refer to low complexity models to establish a first performance estimation of the cooling system. However, as the TAC`s COP is relatively low it has to be carefully design to fit the building. That is why the authors suggest to use reduced high-order models, which account for the most important non-linearity’s of high-amplitude waves but can be integrated with little effort into building performance simulation tools.

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