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OPTIMAL DESIGN OF A STANDING WAVE THERMOACOUSTIC REFRIGERATOR USING GAMS

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Abstract

This work proposes a multi-objective optimization approach to model and optimize small scale standing wave thermoacoustic refrigerator (TAR). This study aims to optimize the geometric variables namely the stack position, the stack length, the blockage ratio and the plate spacing involved in designing thermoacoustic refrigerators. Unlike most previous studies, these variables are considered interdependent. System parameters and constraints that capture the underlying thermoacoustic dynamics have been used to define the models. The cooling load, the coefficient of performance and the acoustic power loss have been used to measure the performance of the device. The optimization task is formulated as a three-criterion nonlinear programming problem with discontinuous derivatives (DNLP). A practical example considering three different gases is given to illustrate the approach. This approach has been implemented in the software GAMS (General Algebraic modelling System) and Pareto optimal solutions describing the most preferred geometry for maximum performance of the device are computed using the augmented ε-constraint method.

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Keywords: Thermoacoustic refrigerator, Coefficient of Performance, Cooling , Multi-objective optimization, ε-constraint method, GAMS.

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1. Introduction

Thermoacoustic refrigerators offer a solution to the current search for alternative refrigerants and alternative technologies (such as absorption refrigeration, thermoelectric refrigeration, pulse-tube refrigeration etc.) to reduce environmental impact[1]. Thermoacoustic refrigerators (Fig. 1) mainly consist of a loudspeaker (a vibrating diaphragm or thermoacoustic prime mover) attached to a resonator filled with gas, a stack usually made of thin parallel plates

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and two heat exchangers placed at either side of the stack. The stack forms the heart of the refrigerator where the heat-pumping process takes place, and it is thus an important element which determines the performance of the refrigerator[2].

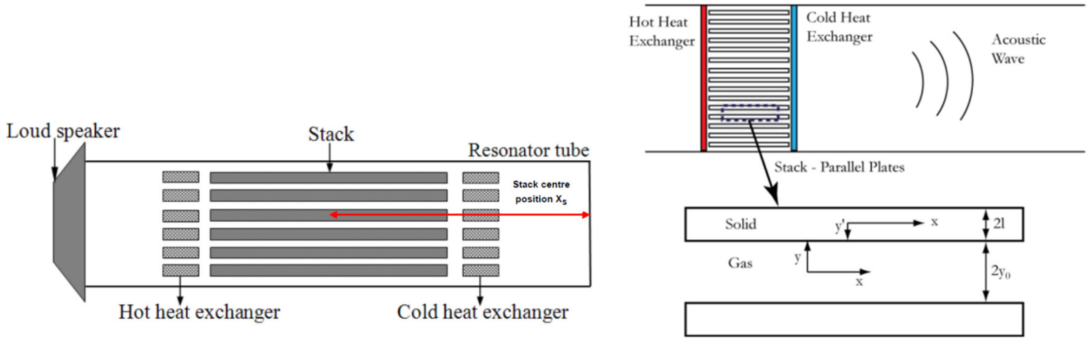


Fig.1: Schematic diagram of a typical thermoacoustic refrigerator.

Using a sound source such as a loudspeaker, an acoustic wave is generated to make the gas resonant. As the gas oscillates back and forth within the chamber, the standing sound wave creates a temperature difference along the length of the stack. This temperature change is a result of compression and expansion of gas by sound pressure and thermal interaction between the oscillating gas and the surface of the plate. Heat is exchanged with the surrounding through heat exchangers at the cold and hot side of the stack[2]. The basic mechanics behind thermoacoustics are already well understood. A detailed explanation of the way thermoacoustic coolers work is given by Swift[2] and Wheatly et al.[3]. Recent researches focuses on improving the performance of the devices so that thermoacoustic coolers can compete with commercial refrigerators.

2. Optimization of thermoacoustic refrigerators

In mathematical sense, optimization is the selection of a best element (with regard to some criteria) from some set of available alternatives. It involves maximizing or minimizing a function of one or more variables. Engineering Optimization is the subject which uses optimization techniques to achieve design goals. It can be defined as the process of finding the conditions that give the maximum or minimum value of a function[4]. The optimization criterion can therefore be formulated in mathematical form, as a function (objective function). This study deals with the application of mathematical programming techniques suitable for the solution of engineering design problems.

Various parameters affecting the performance of the TARs are well understood from previous studies. Some existing efforts include Minner et al.[5] who consider geometric parameters and fluids properties of the system to optimize the coefficient of performance of a TAR. While the Nelder-Mead simplex method is considered to search for a (locally) optimal solution, the model rely extensively upon DELTAE, a black box simulation tool based on linear acoustic theory developed by Swift et al.[2]. Zoontjens et al.[6] demonstrate the optimization of inertance sections of thermoacoustic devices. Individual parameters are varied to determine optimal design using DELTAE. Ueda et al.[7] evaluate how varying certain engine parameters affects pressure amplitudes. Another work that makes use of DELTAE is Tijani et al.[8], who attempt to optimize the spacing of the stack. A systematic design approach that provides fast engineering estimates for initial design calculations of TARs is discussed by Herman and Travnicek[9]. The results found suggest that sets of parameters leading to two seemingly similar outcomes, maximum efficiency and maximum cooling are not the same. With the exception of Minner et al.[5] studies, the previous works vary no more than a single parameter, holding all others constant. The solution approaches that are used guarantee only a locally optimal solution, which may potentially be greatly inferior to a globally optimal solution. In addition, more recently Hariharan N. et al.[10] optimize the parameters like frequency, stack position, stack length, and plate spacing involving in designing TAR using the Response Surface Methodology (RSM). Their results show that geometrical variables chosen for their investigation are interdependent. This is by no means a complete list of the ‘‘optimization’’ of refrigerators components, but it is a good overview of optimization targets.

3. Motivation

Most of the previous optimization efforts rely heavily on studying the effect of a single design parameter on device performance. In all likelihood, each optimal design is a local optimum as the solution obtained is optimal (either maximal or minimal) within a neighbouring set of candidate solution. This is in contrast with the global optimum proposed in this study, which gives global optimal solution among all possible solutions in a specific domain, not just those in particular neighbourhood of variables. We discuss a novel mathematical programming approach to handling design and choice between maximum cooling and maximum coefficient of performance of thermoacoustic refrigerators (TARs). Additionally, we have identified the blockage ratio, the stack spacing, the stack length and the position of the stack as design parameters and take their interdependency into account while computing the optimal set describing optimal performance of TARs unlike previous studies.

The remainder of this paper is organized in the following fashion: in section 4, the model development is presented. The fundamental parameters and equations in our mathematical models characterizing the standing wave thermoacoustic refrigerators are presented. Section 5 describes the proposed optimization approach using GAMS. Section 6 and 7 report the contributions of this work.

4. Model development

The geometry used to derive and discuss the thermoacoustic equations is shown in Fig. 2. The model does not consider any effect of the stack material and the interdependency between the coefficient of performance of thermoacoustic core, the effectiveness of heat exchangers and the acoustic power efficiency. In addition, no attempt is made to derive TAR equations, as detailed derivations of the equations are available in both Mahmud[11] and Tijani[12] thesis.

4.1. Design parameters of the thermoacoustic core

The basic design requirements for thermoacoustic refrigerator are twofold[13]:

(a) To supply the desired cooling load and

(b) to achieve the prescribed cooling temperature at the same time.

The design requirements namely—the drive ratio DR and the normalized temperature difference ΔT_{mn} are respectively 3.5% and 0.030. The coefficient of performance of a thermoacoustic core COP is dependent of nineteen independent design parameters[13]. Herman and Travnicek[9] have collapsed the number of parameters to the following six normalized parameter spaces: Drive ratio DR, normalized temperature difference ΔT_{mn}, normalized thermal penetration depth δ_{kn}, normalized stack length L_{sn}, normalized stack position X_{sn} and blockage ratio BR.

4.2 Objectives functions

The performance of the thermoacoustic stack depends on three main stack design parameters: the centre position, the length and the cross-section area of the stack. The normalized heat flow Φ_H and acoustic power, Φ_W neglecting axial conduction in the working fluid as well as in the stack plates, are given as follows[14]:

$$\Phi_H = -\left[\frac{\delta_{kn} DR^2 \sin(2X_{Sn})}{8\gamma(1+\sigma)\left(1-\sqrt{\sigma}\delta_{kn}+\frac{1}{2}\sigma\delta_{kn}^2\right)}\right] \times \left[\frac{\Delta T_{mn}\tan(X_{Sn})}{(\gamma-1)BR\ L_{Sn}} \times \frac{\left(1+\sqrt{\sigma}+\sigma\right)}{1+\sqrt{\sigma}} - \left(1+\sqrt{\sigma}-\sqrt{\sigma}\delta_{kn}\right)\right] \qquad (1)$$

$$\Phi_W = \left[\frac{\delta_{kn} DR^2 L_{Sn}(\gamma-1)BR \ \cos^2(X_{Sn})}{4\gamma}\right] \times \left[\frac{\Delta T_{mn} \tan(X_{Sn})}{BR \ L_{Sn}(\gamma-1)(1+\sqrt{\sigma})\left(1-\sqrt{\sigma}\delta_{kn}+\frac{1}{2}\sigma\delta_{kn}^2\right)} - 1\right]$$
$$-\left[\frac{\delta_{kn} L_{Sn} DR^2}{4\gamma} \times \frac{\sqrt{\sigma}\sin^2(X_{Sn})}{BR\left(1-\sqrt{\sigma}\delta_{kn}+\frac{1}{2}\sigma\delta_{kn}^2\right)}\right] \quad (2)$$

The normalized cooling load Φ_C and the coefficient of performance of the thermoacoustic core COP are obtained respectively as follows[13]:

$$\Phi_C = \Phi_H - \Phi_W \quad (3)$$

$$COP = \frac{\Phi_H - \Phi_W}{\Phi_W} \quad (4)$$

The cooling load Φ_C is function of 8 non dimensional parameters[9]:

$$\Phi_C = F(\sigma, \ \gamma, \ \varepsilon_S, \ T_{mn}, \ L_{Sn}, \ X_{Sn}, \ BR, \ \delta_{kn}) \quad (5)$$

Where σ, γ, ε_S and T_{mn} represent respectively the Prandtl number, the polytropic coefficient, the stack heat capacity correction factor and the normalized temperature difference. The influence of the working fluid on the gas is exerted through the parameters σ, γ and ε_S.

In the boundary layer approximation, the acoustic power loss per unit area of the resonator is given as follows[14]:

$$\overset{o}{W}_2 = \frac{dW_2}{dS} = \left[\frac{\delta_{kn} DR^2 L_{Sn}(\gamma-1)BR \ \cos^2(X_{Sn})}{4\gamma}\right] + \left[\frac{\delta_{kn} L_{Sn} DR^2}{4\gamma} \times \frac{\sqrt{\sigma}\sin^2(X_{Sn})}{BR\left(1-\sqrt{\sigma}\delta_{kn}+\frac{1}{2}\sigma\delta_{kn}^2\right)}\right] \quad (6)$$

Where the first term on the right-hand side is the kinetic energy dissipated by viscous shear. The second term is the energy dissipated by thermal relaxation.

5. The proposed MMP solution approach to emphasize all objective components

Most of the expressions involved in the formulation of the multi-objective mathematical programming problem (MPF) have been presented in the previous section. We simultaneously consider all three objective components by regarding cooling load (Φ_C), coefficient of performance (COP) and acoustic power lost (W_2) as three distinct objective components to optimize. A single objective optimization analysis shows that these objectives functions are conflicting and thus suitable for a multi-objective optimization approach (details available in Tartibu et. al.[15]). The optimisation task is formulated as a three-criterion nonlinear programming problem with discontinuous derivatives (DNLP) that simultaneously maximise the magnitude of the cooling load (Φ_C), maximise the coefficient of performance (COP) and minimise acoustic power lost (W_2).

$$(MPF) \max_{L_{Sn},X_{Sn},BR,\delta_{kn}} \ \xi = \left\{\Phi_{C(L_{Sn},X_{Sn},BR,\delta_{kn})}, COP_{(L_{Sn},X_{Sn},BR,\delta_{kn})}, -\overset{o}{X}_{2\,(L_{Sn},X_{Sn},BR,\delta_{kn})}\right\} \quad (7)$$

subject to bound limits $\Phi_{C\max}$, $\Phi_{C\min}$, COPC (details available in Tartibu et al.[15] studies) and the following constraint:

$$\Phi_C = \Phi_H - \Phi_W > 0 \quad (8)$$

A negative cooling load does not have any physical meaning and thus the solutions for which Equation 8 is not satisfactory have been eliminated. $(L_{Sn}, X_{Sn}, BR, \delta_{kn})$ in Equation 7 denotes the parameters of the thermoacoustic refrigerator. There is no single optimal solution that simultaneously optimizes all the two objectives functions. In these cases, the decision makers are looking for the “most preferred” solution.

The lexicographic optimisation for each objective function to construct the payoff table for the multi-objective mathematical programming models (MPF) is proposed and implemented in the software GAMS in order to yield only Pareto optimal solutions, avoiding the generation of weak, non-efficient solutions[16]. The advantages of this approach (Augmented ε-constraint method or AUGMENCON) over traditional weighted method and ordinary ε-constraint method can be found in Mavrotas[16], Aghaei et al.[17] and Ahmadi et al.[18] studies. A flowchart of AUGMENCON method is presented in Fig. 2. “p” represents the number of objectives functions, “q” the number of interval and “ni” the index of objective function.

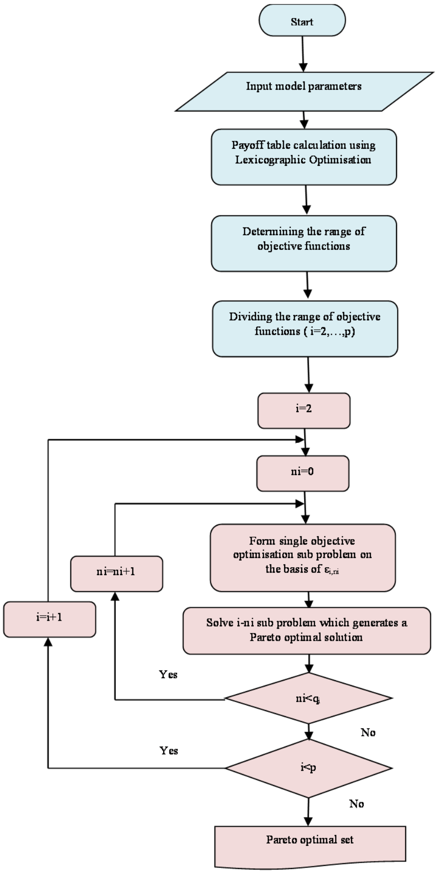


Fig.2: Flowchart of AUGMENCON method for optimization

The code is available in the GAMS library (http://www.gams.com/modlib/libhtml/epscm.htm) with an example. While the part of the code that has to do with the example (the specific objective functions and constraints), as well as the parameters of AUGMENCON have been modified in our case, the part of the code that performs the calculation of payoff table with lexicographic optimisation and the production of the Pareto optimal solutions is fully parameterized in order to be ready to use.

An important aspect of this study is the formulation of the problem. The selection of the primary objective function (most important function) depends on the decision maker. Frequently, this decision is based on problem information and can lead to partial representation of Pareto optimal sets due to the tendency of the solution to cluster toward the maximum of the primary objective function. We have, therefore, articulated the preferences and specifiy limits on objective functions rather than relying on relative importance of objectives as suggested by Marler[19] to identify the best problem formulation. Guidance on the best problem formulation is provided in Tartibu et al.[15]

studies. Subsequently, the augmented ε -constraint method for solving the model (Equation 7) has been formulated as follows:

$$\max\left(\mathrm{COP}_{(L_{Sn},X_{Sn},BR,\delta_{kn})} + \mathrm{dir}_1\ r_1 \times \left(\frac{s_2}{r_2} + \frac{s_3}{r_3} + \frac{s_4}{r_4} + \frac{s_5}{r_5} \right) \right) \tag{9}$$

Subject to

$$\Phi_{C(L_{Sn},X_{Sn},BR,\delta_{kn})} - \mathrm{dir}_2\ s_2 = \varepsilon_2$$

$$\overset{o}{W}_{2(L_{Sn},X_{Sn},BR,\delta_{kn})} - \mathrm{dir}_3\ s_3 = \varepsilon_3$$

$$s_i \in \Re^+$$

where dir_i is the direction of the ith objective function, which is equal to -1 when the ith function should be minimised, and equal to +1 when it should be maximised. Efficient solutions to the problem are obtained by parametrical iterative variations in the ε_i. s_i are the introduced surplus variables for the constraints of the MP problem. $r_1\ s_i / r_i$ are used in the second term of the objective function in order to avoid any scaling problem. The following constraints (upper and lower bounds) have been enforced on variables in order for the solver to search for the optimal solutions in those ranges:

$X_{Sn}.\mathrm{lo} = 0.010;\ \ X_{Sn}.\mathrm{up} = 1.000$

$BR.\mathrm{lo} = 0.700;\ \ BR.\mathrm{up} = 0.900;$

$\delta_{kn}.\mathrm{lo} = 2\delta_k;\ \ \delta_{kn}.\mathrm{up} = 4\delta_k;$ with δ_k representing the thermal penetration depth.

Efficient solutions for the proposed model have been found using the AUGMENCON method and the LINDOGLOBAL solver. To save computational time, the early exit from the loops as proposed by Mavrotas[16] has been applied. The range of each five objective functions is divided into four intervals (five grid points). The normalised stack length (L_{Sn}) has been arbitrarily given successive values of 0.05-0.1-0.15-0.2-0.25-0.3-0.35-0.4-0.5. This process generates optimal solutions corresponding to each value of L_{Sn}. The maximum CPU time taken to complete the results is 324.981 sec.

6. Results and discussion

The influence of the working fluid (randomly selected from Tijani[12] studies) on the performance of TAR has been investigated. Equation 6 shows the negative effect of viscosity on the performance of TAR. A reduction of the effect of viscosity will result in an increase in efficiency. This can be done by decreasing the Prandtl number σ. The Prandtl number is an important parameter in thermoacoustics as can be seen from Equation 1 and Equation 2. Values of Prandtl number calculated by Tijani[12] for binary gas mixtures are presented in Table 1. These Prandtl number values have been incorporated in the models to predict the performance of the TAR for different gas mixtures.

Table 1: Working fluids specifications.

Working fluid		He	He-Ne	He-Xe
Prandtl number	σ	0.67	0.53	0.27
Ratio c_p/c_v	γ	1.63	1.64	1.67

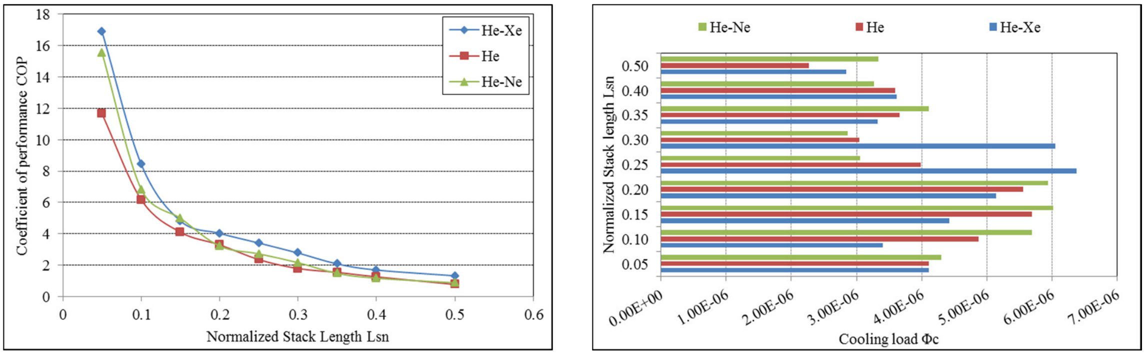
Fig. 3a and Fig. 3b represent graphically the results obtained in Table 2 and Table 3. These results show that there is a distinct optimum when considering the design for maximum coefficient of performance (COP) and maximum cooling load (Φ_C) for different working fluids. The best configuration has been highlighted in bold as guidance for a decision maker. These results suggest that the highest COP and Φ_C will be obtained with a mixture of He-Xe. Interestingly, similar trends have been obtained by Wetzel and Herman[13] and Herman and Travnicek[9] using a systematic design approach. Optimal parameters describing the geometry of the device (BR, δ_{kn} , X_{Sn} and L_{sn}) are also reported. The results demonstrate that the highest COP is expected by locating the stack centre position closer (as compared to the cooling load) to the pressure antinode (closed end) and making the stack length L_{sn} shorter. Based on Table 2, Table 3 and Fig. 3, one will suspect that the normalized stack length L_{Sn} , the normalized stack position X_{Sn} , the blockage ratio BR and the normalized thermal penetration depth δ_{kn} are somehow related. Indeed, that is the case.

Table.2: Non-dominated solutions obtained for maximum COP using AUGMENCON.

	Lsn	**0.050**	**0.100**	**0.150**	**0.200**	**0.250**	**0.300**	**0.35**	**0.4**	**0.5**
He	BR	**0.720**	0.900	0.835	0.890	0.760	0.860	0.817	0.728	0.808
	δkn/10	**0.089**	0.082	0.060	0.460	0.046	0.046	0.046	0.046	0.046
	Xsn	**0.413**	0.521	0.503	0.575	0.610	0.610	0.610	0.517	0.610
	Φc	**4.11E-0.6**	4.87E-06	3.74E-06	2.54E-06	2.47E-06	2.33E-06	2.33E-06	2.12E-06	1.31E-06
	COP	**11.65**	6.176	4.109	3.306	2.362	1.795	1.795	1.271	0.778
He-Ne	BR	**0.700**	0.900	0.700	0.820	0.836	0.878	0.862	0.848	0.807
	δkn/10	**0.046**	0.069	0.046	0.070	0.046	0.046	0.055	0.044	0.046
	Xsn	**0.359**	0.620	0.481	0.466	0.665	0.634	0.737	0.728	0.708
	Φc	**2.81E-06**	4.22E-06	3.31E-06	3.87E-06	2.76E-06	2.86E-06	3.26E-06	2.21E-06	1.59E-06
	COP	**15.529**	6.838	4.999	3.225	2.732	2.169	1.484	1.179	0.882
He-Xe	BR	**0.700**	0.856	0.900	0.700	0.787	0.843	0.745	0.821	0.757
	δkn/10	**0.048**	0.051	0.046	0.048	0.046	0.048	0.046	0.046	0.046
	Xsn	**0.414**	0.577	0.672	0.506	0.657	0.693	0.639	0.693	0.659
	Φc	**2.73E-06**	3.41E-06	3.25E-06	3.04E-06	3.09E-06	4.16E-06	2.76E-06	2.65E-06	2.84E-06
	COP	**16.873**	8.435	4.826	4.336	3.419	2.782	2.088	1.700	1.332

Table.3: Non-dominated solutions obtained for maximum Φc using AUGMENCON.

	Lsn	**0.050**	**0.100**	**0.150**	**0.200**	**0.250**	**0.300**	**0.35**	**0.4**	**0.5**
He	BR	0.720	0.900	**0.900**	0.900	0.900	0.900	0.700	0.835	0.700
	δkn/10	0.089	0.082	**0.083**	0.084	0.070	0.059	0.078	0.078	0.048
	Xsn	0.413	0.521	**0.561**	0.582	0.656	0.609	0.489	0.628	0.519
	Φc	4.11E-06	4.87E-06	**5.70E-06**	5.56E-06	3.99E-06	3.04E-06	3.66E-06	3.59E-06	2.27E-06
	COP	11.65	6.176	**3.429**	2.427	2.118	1.361	1.324	0.928	0.455
He-Ne	BR	0.788	0.900	**0.700**	0.900	0.900	0.900	0.900	0.839	0.900
	δkn/10	0.089	0.081	**0.092**	0.083	0.047	0.048	0.065	0.071	0.092
	Xsn	0.451	0.544	**0.478**	0.611	0.664	0.635	0.644	0.620	0.661
	Φc	4.30E-06	5.70E-06	**6.01E-06**	5.94E-06	3.06E-06	2.86E-06	4.11E-06	3.27E-06	3.33E-06
	COP	11.757	5.773	**3.807**	2.725	2.643	2.024	1.223	1.096	0.694
He-Xe	BR	0.900	0.856	0.900	0.900	**0.900**	0.861	0.900	0.716	0.757
	δkn/10	0.066	0.051	0.062	0.070	**0.092**	0.092	0.048	0.066	0.046
	Xsn	0.501	0.577	0.670	0.693	**0.707**	0.692	0.822	0.596	0.659
	Φc	4.11E-06	3.41E-06	4.42E-06	5.14E-06	**6.38E-06**	6.05E-06	3.32E-06	3.62E-06	2.84E-06
	COP	16.100	8.435	4.418	3.973	**2.684**	2.455	2.076	1.692	1.332



(a) (b)

Fig. 3: (a) COP function of normalised stack length and (b) Φ_C function of normalised stack length.

7. Conclusion

In this paper, a multi-objective approach that provides fast initial engineering estimates to initial design calculation of thermoacoustic refrigerators is discussed. Their performances were evaluated using three criteria: 1) maximum cooling, 2) best coefficient of performance, and 3) the acoustic power loss. Four different parameters - stack length, stack centre position, stack spacing and blockage ratio - describing the geometry of the device have been studied. Nonlinear programming models with discontinuous derivatives (DNLPs) have been formulated and implemented in GAMS. For the case of multiple objectives considered simultaneously, we have applied an improved version of a multi-objective solution method, the ε-constraint method called augmented ε-constraint method (AUGMENCON). We have adopted a lexicographic method in order to avoid dominated Pareto optimal solutions. For different arbitrary values of stack length, this process generates optimal solutions describing geometry of the TAR, solutions which depend on the a priori design goal for maximum cooling or maximum coefficient of performance. This present study reveals the suitability of a multi-objective optimization approach to model and optimize a TAR using the software GAMS. The results found shows that there is a specific stack length which corresponds to a specific stack centre position, specific stack spacing and a specific blockage ratio depending on the design goal.

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