OPTIMIZATION OF INDUSTRIAL DESIGN PARAMETERS AND SYSTEM OPERATION PARAMETERS OF REGENERATOR OF THERMO-ACOUSTIC REFRIGERATOR BASED ON CUCKOO OPTIMIZATION HEURISTIC ALGORITHM

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Thermo-acoustic refrigeration technology is one of the new refrigeration technologies which is supposed to supersede the traditional refrigeration technology in the era of technology breakthrough, because it has the advantages of environment-friendly working medium, no mechanical parts movement, less metal loss, simple structure and easy maintenance. The low coefficient of refrigeration hinders the application and development of thermo-acoustic refrigeration technology. Therefore, the optimization of thermo-acoustic system and its core component recuperator is the top priority of current research. In this article, cuckoo optimization algorithm is introduced to optimize the cooling coefficient and cooling power of the regenerator. The optimization parameters are the length, center position, porosity and driving ratio of the regenerator. Compared with the results of published literature, cuckoo optimization algorithm obtains better results. Compared with the Drosophila optimization algorithm, the optimal COP *obtained in this paper is increased by 15%. It is not difficult to see from the research results that the Rhododendron optimization algorithm is quite suitable for solving the optimization design of thermo-acoustic refrigerator.*

Keywords: Thermo-acoustic refrigerator, Cuckoo Search algorithm, Stack unit.

1. Introduction

Thermo-acoustics is a complex subject including thermodynamics and acoustics, which mainly studies the thermo-acoustic effect, that is, the conversion of sound energy into heat energy or heat energy into sound energy, that is, the physical phenomenon of acoustic self-excited oscillation caused by heat energy in inert gas working medium. Thermo-acoustic refrigerator is a kind of refrigeration equipment based on thermo-acoustic reverse effect. The advantage of thermo-acoustic refrigeration technology is that its working medium is environment-

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friendly working gas such as air or inert gas [1], and it does not rely on mechanical parts to do work, and does not need to consider the problem of metal loss. The composition of the equipment is simpler than that of the traditional refrigerator and the maintenance cost is lower. It is regarded as the most potential alternative to the traditional refrigerator Technology of refrigeration equipment [2].

Although the design theory of thermo-acoustic system has made great progress in the past 30 years, it has not got a breakthrough development. Compared with the traditional refrigerator, the coefficient of performance of thermo-acoustic refrigerator is lower in practical application. Therefore, the optimization design of the thermo-acoustic system is the key task to make it large-scale civil [3-6].

In recent 30 years, for increasing the productivity of thermo-acoustic refrigeration system and key components, a large number of operation parameters and geometric parameters have been optimized [7]. In terms of geometric parameter optimization, many research groups use delta e or finite element method [8] based on linear thermo-acoustic theory [9]. In terms of operation parameter optimization, Miner [10] and Nsoor [11] Studied the Influence of working medium on system, Through many comparative experiments, Chen concluded that the system would work best at a certain frequency [12].

In recent years, researchers in various countries have used different algorithms to optimize the thermo-acoustic system. Chaitou [13] used PSO algorithm to optimize thermo-acoustic engine for the first time. Zolpakar [14] team used genetic algorithm to optimize the regenerator in the thermo-acoustic refrigerator, the refrigeration coefficient optimization result reached 1.58. Anas A [15] and others used the Drosophila optimization algorithm to optimize the mathematical model of the thermo-acoustic refrigerator, taking the refrigeration coefficient and refrigeration power as the objective function respectively, and the optimal refrigeration coefficient was 1.8 and the optimal refrigeration power was 16.85W.

In this study, using cuckoo optimization algorithm to improve the performance of thermo-acoustic refrigerator system from two single objective schemes of refrigeration coefficient and refrigeration power, and the optimization results are compared with the previous literature optimization results. The optimized regenerator length, center position, porosity, driving ratio, cooling power and cooling coefficient were compared.

2. Model

2. 1 *System structure simulation diagram*

Fig 1 is mechanism simulation diagram of thermo-acoustic refrigeration system, which is composed of loudspeaker, stack, resonator and heat exchanger. The left end of the driving room is equipped with a loudspeaker which provides the driving source, and the right end is a rigid closed cone-shaped buffer volume.

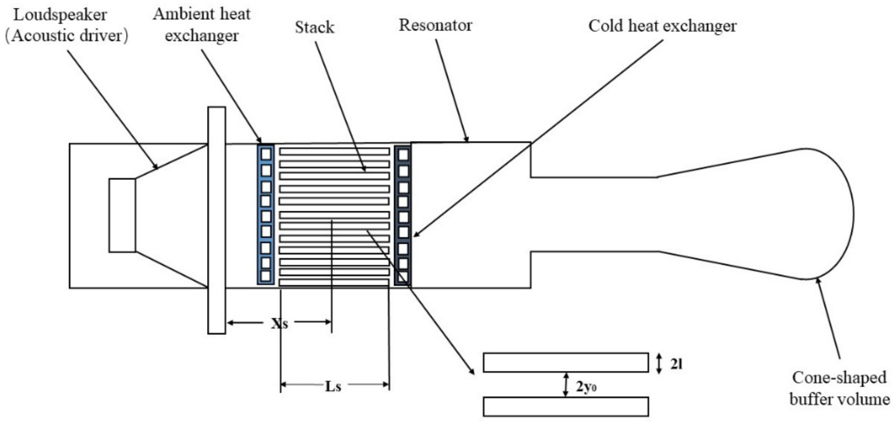

Fig. 1 TR System structure simulation diagram

The resonator is the core of the thermo-acoustic refrigerator. The gas in the resonator periodically compresses and expands, forming a thermal cycle, and forming a temperature difference at both ends of the regenerator [16].

2. 2 *Normalized parameters of thermo-acoustic refrigerator*

Table 1

Normalized parameters in the optimization design of thermo-acoustic refrigerator

<table>
<tr><th colspan="2">Normalized processing data</th></tr>
<tr><td rowspan="2">Acoustic and thermodynamic data</td><td>$\mathrm{DR} = P_0/P_m$
$Q_{cn} = Q_C/P_m aA$
$W_{acn} = W_{ac}/P_m aA$
$(\Delta T_{mn}) = \Delta T_m/T_m$</td></tr>
<tr><td>$\delta_{kn} = \delta_k/y_0$
$\delta_{vn} = \delta_v/y_0$</td></tr>
<tr><td>Physical structure data</td><td>$L_{sn} = \mathrm{k} * L_s$
$X_{sn} = \mathrm{k} * X_s$
$\mathrm{B} = y_0/y_0 + 1$</td></tr>
</table>

The cooling performance of a thermo-acoustic refrigerator is affected by many factors, such as acoustic, thermodynamic data and the physical structure data. Because there are many variable parameters, the calculation formula of refrigeration coefficient is more complex and the amount of calculation is huge, so the actual variables can be transformed into normalized variables by parameter normalization to reduce the workload and simplify the calculation. According to the linear thermo-acoustic theory and short plate stack approximation model [16] proposed by Tijani et al. The parameter normalization is shown in Table 1.

In order to compare this research work, the research work published by zolpakar et al. In 14 years was selected as the contrast object, and the same conditions and constraints were selected [17]. Zolpakar's team used GA to calculate the thermo-acoustic mathematical model, and the COP increased from 1.3 to 1.58. For the first time, cuckoo algorithm is used to optimize the cooling coefficient and cooling power of the regenerator of the thermo-acoustic system.

3. Cuckoo optimization algorithm

Cuckoo algorithm is a kind of swarm intelligence search technology which integrates cuckoo brooding behavior and Levy flights mode. It searches an optimal nest by random walk to hatch its own eggs. This method can quickly and effectively find the optimal solution of the problem or equation, and has strong global optimization ability.

3. 1 *Brooding behavior of cuckoos*

In 2009, Xin She Yang and Suash Deb proposed cuckoo algorithm (CS) in cuckoo search via Levy flights [18]. The most special habit of cuckoos is to nest and lay eggs. Because there is no hatching behavior, some cuckoos in nature will lay their eggs in parasitic nests and rely on their parents to hatch and raise their nests. In order not to be noticed by the host, the cuckoo will remove one or more eggs from the host before laying eggs, so that the number of eggs in the nest is equal or similar[18]. Host birds will discard cuckoo eggs or rebuild their nests directly when they find strange eggs in the nests.If an exotic egg is found, the nest owner will rebuild a nest. it can be considered that the nest and egg are used to refer to the solution of the problem to be solved, and whether the egg can be hatched and thrive by the host bird is the only criterion to judge whether the solution is good or not. The process of cuckoo looking for nest and laying eggs is the process of finding solutions in n-dimensional space [18].

3. 2 *Levy flight*

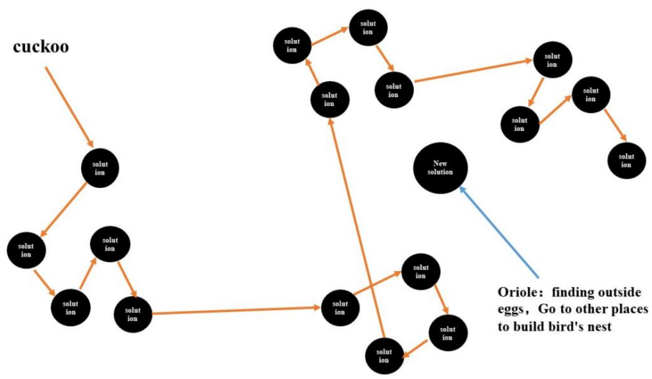

Fig. 2 Levi flight

Levi flight is a kind of non Gaussian stochastic process, and its steady increment is subject to the stable distribution of Levi. In the flight process, the short distance walk with smaller step length and the long distance walk with occasional larger step length alternate, which is conducive to increase population diversity and expand the search range, and not fall into local optimal.

Cuckoos find their nests and lay eggs by using Levy flight [18], as shown in Fig. 2, which is a kind of walking position between long step and short step. Therefore, the formula of using Levy flight to update the nest position is defined as follows:

$$X_{t+1} = X_t + \alpha \cdot * Levy(\beta), \quad (1)$$

α is the step size scaling factor, $Levy(\beta)$ Levy is random path.

3. 3 *Governing equations and Solutions*

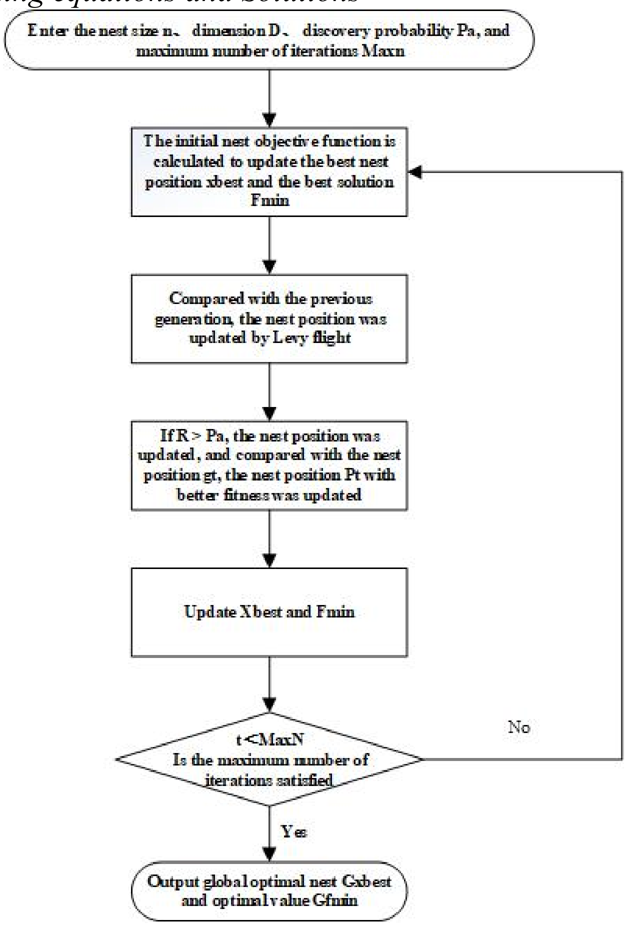

Fig 3 cuckoo optimization algorithm flow chart

The normalized enthalpy flow (cooling power) of thermo-acoustic refrigerator is expressed as Q_{cn}, and the normalized consumed acoustic work is expressed as W_{acn}. Tijani et al defined the normalized cooling power and the normalized consumed sound power respectively with the normalized parameters in 2002 [16]. Then, the cuckoo optimization algorithm is implemented to solve the control equations within the constraints under the iteration and termination conditions.

$$Q_{cn} = \frac{\delta_{kn} DR^2 \sin(2X_{sn})}{8\gamma(1+\sigma)G} \times \left[\frac{\Delta T_{mn} \tan(X_{sn})}{(\gamma-1)BL_{sn}} \frac{1+\sqrt{\sigma}+\sigma}{1+\sqrt{\sigma}} - \left(1+\sqrt{\sigma}-\sqrt{\sigma}\delta_{kn}\right) \right], \quad (2)$$

$$W_{acn} = \frac{\delta_{kn} L_{sn} DR^2}{4\gamma}(\gamma-1)B\cos^2(X_{sn}) \times \left[\frac{\Delta T_{mn} \tan(X_{sn})}{BL_{sn}(\gamma-1)\left(1+\sqrt{\sigma}\right)G} - 1 \right] - \frac{\delta_{kn} L_{sn} DR^2}{4\gamma} \frac{\sqrt{\sigma}\sin^2(X_{sn})}{BG}, \quad (3)$$

$$G = 1 - \sqrt{\sigma}\delta_{kn} + \frac{1}{2}\sigma\delta_{kn}^2, \quad (4)$$

$$COP = \frac{Q_{cn}}{W_{acn}}, \quad (5)$$

3. 4 *Define objective function*

Table 2

Optimization variable range

Normalized variable	Constraint
L_{sn}	$0 \le L_{sn} \le 1$
X_{sn}	$0.06 \le X_{sn} \le 0.42$
B	$0.67 \le B \le 0.8$
DR	$0.015 \le DR \le 0.03$

Table 3

System parameters [19]

Considered parameters	Value
System working environment parameters	$P_m = 10bar$ $T_m = 250K$ $\Delta T = 75K$ $f = 400Hz$

Physical parameters of working fluid	$a = 935\, m/s$ $\sigma = 0.68$ $\gamma = 1.67$ $k = 2.68 m^{-1}$ $\delta_{kn} = 0.66$

The objective function studied in this paper is a four-dimensional search space problem. The four parameters are the length of normalized regenerator, the center position, porosity and driving ratio of normalized regenerator, as shown in Table 2. The research of Tijaniet [16] and Zolpakar [14] shows that these four parameters have a crucial influence on the target functions COP and Q_{cn}. Table 3 shows the fixed operating parameters in the target function and the thermal physical parameters of the working medium.

4. Optimization results and research

4. 1 *Optimizing* COP

Table 4

Comparison of different optimization schemes for single objective COP

Optimal results	Zolpakar（GA）[14]	Anas A. Rahm(FOA)[15]	Current work（CS）
L_{sn}	0.26	0.096	0.06
X_{sn}	0.21	0.093	0.05
B	0.731	0.68	0.75
DR	0.023	0.016	0.242
COP	1.5	1.83	2.12
$Q_c(W)$	4.87	1.041	1.28
$W_{ac}(W)$	3.60	0.568	0.60

Table 5

Optimization results of single objective cop with cuckoo optimization algorithm

	1	2	3	4	5	6	7	8	9
L_{sn}	0.21	0.19	0.16	0.14	0.063	0.12	0.10	0.07	0.08
X_{sn}	0.19	0.17	0.12	0.11	0.062	0.10	0.08	0.06	0.07
B	0.79	0.77	0.77	0.75	0.75	0.72	0.76	0.74	0.73
DR	0.0297	0.0284	0.0281	0.0263	0.0242	0.0278	0.0281	0.0281	0.0294
COP	1.47	1.64	1.72	1.97	2.12	1.84	1.77	1.61	1.55
$Q_c(W)$	7.4	5.7	4.8	2.4	1.28	3.3	3.1	5.4	6.5
$W_{ac}(W)$	5.03	3.47	2.79	1.22	0.60	1.79	1.75	3.35	4.2

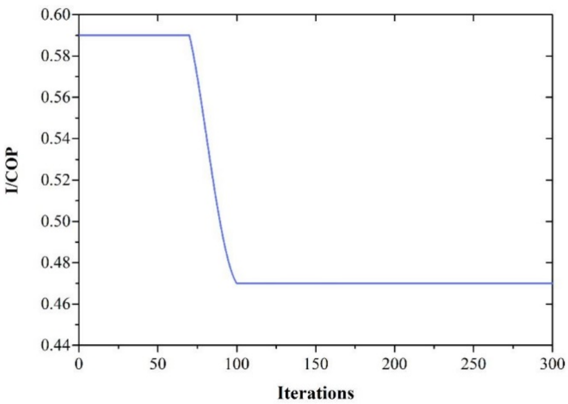

Fig 4 objective function and iteration curve

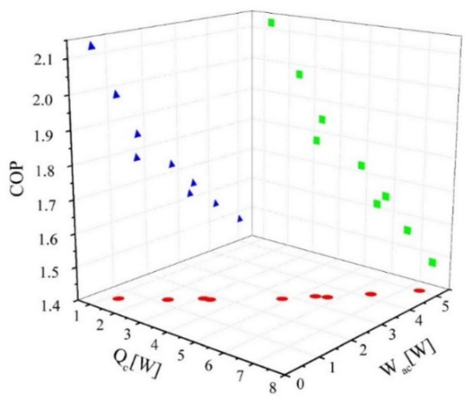

Fig 5 3D diagram of refrigeration coefficient, refrigeration power and consumed sound power

As shown in Fig 4, after iterative optimization using cuckoo optimization algorithm, the final convergence is 0.471, that is to say, the best COP is 2.12. It can be seen from Figure 5 that COP an Q_c do show a contradictory trend as mentioned by Herman et al[20], and it can be noted that the cooling power is proportional to the consumed sound power, while a higher COP can be obtained at a lower sound power consumption[20].

In order to facilitate comparison, this paper uses the operation parameters and constraints of published literature for numerical optimization. After comparing the optimization results of this paper with those of Zolpakar [14] et al. Using genetic algorithm and Anas A. Rahman [15] et al. Using fruit fly optimization algorithm, table 4 shows that Cuckoo optimization algorithm can obtain higher cop under the same operation conditions and constraints, It shows that Cuckoo optimization algorithm can provide a better ideal solution. Compared with the work of Zolpakar et al., COP increased from 1.35 to 2.12, with a growth rate of 57%. Compared with the work of Anas A. Rahman et al., COP increased from 1.83 to 2.12, with a growth rate of 15%. Comparing the length and center position of regenerator with different refrigeration coefficient in Table 5, it can be found that the higher the refrigeration coefficient, the lower the length and center position of regenerator. Optimization cases in Table 5 can offer more possibilities for designers to deal with different design requirements and design backgrounds.

4. 2 *Optimizing* Q_{cn}

Table 6

Comparison and verification of achievements

Optimal results	Anas A（FOA）	Current work（CS）
L_{sn}	0.39	0.41
X_{sn}	0.28	0.32
B	0.79	0.77
DR	0.0295	0.028
COP	1.02	1.01
$Q_c(W)$	16.85	19.08
$W_{ac}(W)$	16.48	18.89

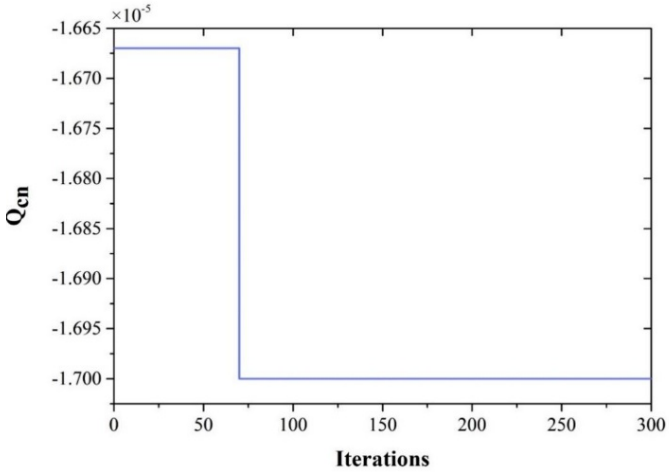

Fig 6 objective function and iteration curve

The second part of this study is to optimize the cooling power. As shown in Fig 6, Q_{cn} converges to - 1.70 * 10^{-5}, that is to say, the cooling power is 19.08W, which is similar to Anas a Compared with Rahman's work, the cooling power is increased from 16.85W to 19.08W, with a growth rate of 19%, which proves that the Cuckoo optimization algorithm has excellent performance when the cooling power is taken as the optimization target. Therefore, Cuckoo optimization algorithm can be considered to obtain the optimal solution in the design of those small refrigeration equipment which pay more attention to the refrigeration power.

5. Conclusion

In this study, Cuckoo optimization algorithm is used to calculate the mathematical model of thermo-acoustic system. The research work is divided into two parts, which are the optimization of the cooling power and the cooling coefficient.

The four optimization variables are regenerator length, regenerator center position, porosity and drive ratio. Compared with Herman's research results, the trend of the inverse ratio of cooling power and cooling coefficient is more significant. In the optimization calculation with the coefficient of refrigeration as the objective function, the coefficient of refrigeration finally converges to 2.12, with a growth rate of 57% compared with the work of Zolpakar et al. And a growth rate of 15% compared with the work of Anas A. Rahman et al. In the second part of the research work, the cooling power converges to 19.08W quickly, which is 19% higher than that of Anas A. Rahman et al. Based on the calculation results of Cuckoo optimization, the optimization effect of cuckoo optimization method on refrigeration coefficient and refrigeration power is verified, which is better than the results in references.

In the future optimization research, we will try to study and optimize the mathematical model of the new thermo-acoustic system, and discuss the influence of other variables in the system on the function of the whole machine, and the optimization design will be verified by physical experiments.

Nomenclature

DR Drive ratio
P Pressure (Pa)
Q Cooling power (W)
a Sound velocity (m/s)
A Area (m^2)
W Acoustic work (W)
B Blockage ratio or porosity
c_p Specific heat of stack (J/kg.K)
k Thermal conductivity of gas (W/mK)
L Length of stack (m)
T Temperature (K)
x Center position of stack (m)
yo Half plate spacing of stack (m)
f frequency (Hz)

Greek Symbols

δ Penetration depth (m)
γ Ratio of isobaric to isochoric specific heat
ρ Density of stack material (kg/m3)
σ Prandtl number
ω Angular velocity (rad/s)
μ Dynamic viscosity (Pa.s)
ΔT Temperature difference(K)

Subscript and Superscipt

c Cool end
k Thermal
n Normalized value
m Mean value
s Stack
v Viscous
0 Amplitude
ac Acoustic work

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