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SIMULTANEOUS ALGORITHM FOR ACHIEVING INTELLIGENT CONSTRUCTION OF ORC CONFIGURATION AND FLUID SELECTION

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ABSTRACT

Configuration and working fluid are the two important factors that influence Organic Rankine Cycle (ORC) performance. Superstructure technology, which contains as much as possible ORC architecture features, is considered as cutting-edge artificial design technology to ORC configuration, however, it leads to intrinsic difficulty for modelling and calculation. In order to overcome the weakness and to achieve structure construction and fluid selection simultaneously, a nested three-level algorithm employing evolutionary algorithm, sequence quadratic programming (SQP) and 0-1 programming is proposed. Based on HEATSEP simplification method developed by Lazzaretto, ORC structure with different architecture features is decomposed into several elementary cycles sharing one to three of four thermodynamic processes, and this form of combination for elementary cycles is called topology combination. By using real number coding for design parameter and binary coding for topology parameter, evolutionary algorithm based on computational intelligence is adopted to generate ORC structure without artificial design. Using 0-1 programming with working fluid selection coefficient in the outer-level algorithm, simultaneous achievement of fluid optimization and structure design of ORC is realized. A case study is done after verifying accuracy of the algorithm by reference data, with a predefined set of 13 organic fluids. The results show that both intelligent construction for ORC structure and selection of optimum pure organic fluid can be achieved by the algorithm preliminarily in terms of maximum net power output.

Keywords: Simultaneous optimization, intelligent construction, fluid selection, evolutionary algorithm, SQP, 0-1 programming

NONMENCLATURE

Abbreviations	
ORC	Organic Rankine Cycle
SQP	sequence quadratic programming
TCRC	Two-stage condensation ORC
LNG	Liquefied natural gas
NG	Natural gas
Symbols	
x	Working fluid selection coefficient

1. INTRODUCTION

Increasing depletion of fossil fuels, such as coal, oil and nature gas, has brought about a wide range of concern in global warming, climate change, energy crisis and environment pollution problems among international community. To tackle with these issues, countries around the world are enlarging the account of renewable energy in energy consumption structure, and endeavoring to increase the utilization efficiency of fossil fuels by improving performance of energy system and recovering waste heat. Due to their low-grade-energy property, traditional power cycle could not exploit the potential of industry waste heat, engine exhaust and renewable energy such as solar energy, geothermal energy, biomass energy etc. [1], which causes an urgency of technology for low grade heat source. Among the available mature and cutting-edge technologies, such as Kalina cycle, Trilateral Flash cycle, Organic Rankine cycle (ORC) and supercritical cycle, ORC is expected to produce 15-50% more power output under the same heat [2]. Compared with traditional Rankine cycle using water/steam as working fluid, organic fluids characterized by low boiling point are employed by ORC, which make it possible to generate power of middle-low temperature heat. Besides, with the advantages of low maintenance, easy operation, low running cost and long life-span, ORC has been gaining more and more attention.

The configuration and working fluid are the two important aspects that influence ORC performance [3, 4]. Conventional method to confirm ORC configuration generally has two steps: ORC structure design and following with parameter optimization. In the design phase, only one or two architecture features are taking into account, which contribute to the improvement of ORC performance. For instant, Saleh[5], Dai[6] and Li[7] designed and analyzed the ORC with recuperator and superheated features; Meinel[8] designed and analyzed the ORC with regenerative and turbine bleeding features; Fischer[9] designed and analyzed the trilateral ORC cycle; Schuster[10] designed and analyzed transcritical and supercritical ORC cycle; Stijepovic[11] designed and analyzed the ORC with multiple evaporation pressure; Bao[12] designed and analyzed the ORC with zeotropic mixture and two-stage condensation pressure, and Li[13] designed and analyzed the cascade ORC cycle. Though all the architecture features in the mentioned literature are beneficial to ORC, it cannot be all included in by conventional design method. Therefore, superstructure method has appeared.

An ORC superstructure is a set of as much as possible ORC configurations, which usually contains more architecture features. Lee [14] proposed a superstructure of cryogenic ORC imbedding about 1024 possible alternatives. Kermani [15] proposed an ORC superstructure including features of turbine bleeding, regenerative and transcritical cycle. Bao [16] proposed a cryogenic ORC superstructure of three-stage condensation and expansion pressure. Although superstructure method provides a new idea for ORC configuration design, its intrinsic complexity would cause high difficulty and cost of calculation, and specific superstructure need to be constructed for different applications. In order to overcome the weaknesses of superstructure method, some researchers have proposed superstructure-free method, shown in Table 2.

Voll [17] proposed the superstructure-free synthesis and optimization method for distributed energy supply system by exploiting evolutionary algorithm. Wang [18] used superstructure-free method to achieve multi-objective synthesis and optimization of thermal power plants. Toffolo [19, 20] proposed the superstructure-free method for Rankine cycle and ORC with specific working fluid. The algorithms in those researches are evolutionary algorithm, which is a part of computational intelligence [21] and can realizes intelligent construction without artificial design or constructing superstructure.

As working medium, organic fluid plays a so nonnegligible role in ORC performance that cannot be ignored in the stage of ORC design [22]. However, the structure of thermodynamic cycle was constructed with specific working fluid in the above related literature, where ORC working fluid selection is not included. Therefore, taking working fluid selection into consideration, this paper proposes a method for intelligent construction of subcritical ORC, which can achieve simultaneous optimization for cycle structure and working fluid. The connotation of intelligent construction is machine design of ORC structure through codification of necessary parameters, considering as much as possible solutions with more architecture features.

Table 1 Superstructure-free method for energy system

Ref.	Objection	Algorithms	Working fluid	Specific application
[17]	Distributed industry energy supply system	Evolutionary algorithm	N/A	Industry energy supply
[18]	Thermal power plant	Evolutionary algorithm	N/A	Power generation
[19]	Rankine cycle	Evolutionary algorithm	Water	Power generation
[20]	ORC	Evolutionary algorithm	R245fa	Geothermal power generation

2. THEORY FOR CODIFICATION

2.1 Simplifying basis

Heat transfer section tends to conceal the basic layouts of thermodynamic cycles. There have been some efforts to simplify the design and optimization of energy conversion system. Among them, the method named HEATSEP[26, 27], which separates the definition of heat transfer network from the definition of the rest of the system and insulates all the heat transfer processes in an undefined “black-box”, has shown its practicability. In HEATSEP method, heat transfer processes are isolated from other thermodynamic processes and represented by so-called “thermal cuts”, which are served as placeholders. Only the state parameters, like T, P, mass flow rate and etc., at the two ends of each thermal cut are concerned about. Thus, the basic layouts of thermodynamic cycles appear more clearly. The specific layout of heat transfer network can be figured out by mature technologies for heat exchange network synthesis. HEATSEP method simplifies the design problem of thermodynamic cycles into two sub-problems, one is the structure composed by components except heat exchangers and another is the synthesis of heat transfer network.

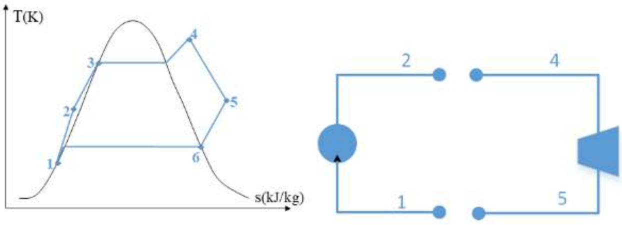


Fig.1 Simplification of simple ORC on HEATSEP

By HEATSEP method, simple ORC cycle which includes basic four thermodynamic processes can be simplified into the simple form called elementary cycle, as shown in Fig.1. Accordingly, ORC with different architecture features can be decomposed into several elementary cycles by sharing one to three of four thermodynamic processes with mixers and splitters, which is called topology combination consisting of thermal cuts, mixers, splitters and the rest part of thermodynamic cycles. By mixing working fluids of each elementary cycle through mixers before the beginning of thermodynamic process, and by splitting working fluids of each elementary cycles through splitters after the ending of thermodynamic process, elementary cycles with different mass flow rates of working fluid share one of the four thermodynamic cycles.

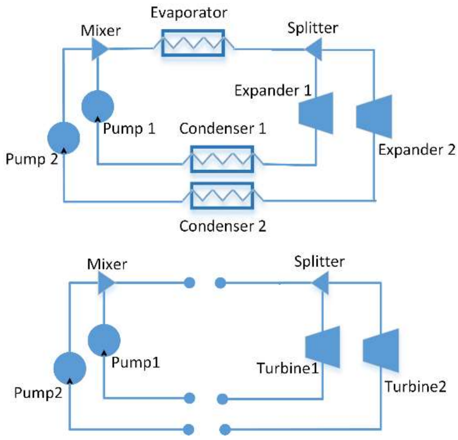


Fig.2 Illustration of topology combination

Take the following two-stage condensation ORC in Fig.2 for example to illustrate topology combination. This configuration of ORC is decomposed into two elementary cycles by HEATSEP method. Through one mixer and one splitter, the two elementary cycles share heating process while other processes carry out independently.

2.2 *Coding method*

Generally, T-s diagram or P-h diagram is used to analyze ORC cycle in terms of thermodynamics. Once the initial state of compression and expansion are determined, the final state of them are then decided with isentropic efficiencies. Consequently, evaporation and condensation pressure are determined with fixed degree of superheat and degree of sub-cooling. So, four real variables of each elementary cycle are included in the codification of design parameter, that is the thermodynamic parameters at the initial state of compression process and expansion process describing by a matric composed of T-s or P-h parameter:

$[T_c, s_c, T_e, s_e]$ or $[P_c, h_c, P_e, h_e]$

where the subscript c and e represent compression process and expansion process respectively.

The nature of ORC topology combination is the sharing among several elementary cycles for each thermodynamic process, so topology parameter consists of four row vectors of binary variables corresponding to each specific thermodynamic process. Suppose that A, B C, D represent compression process, heating process, expansion process and cooling process respectively. The length for each row vector shows the gross number of elementary cycles; the value of 0 means the elementary cycles carries out the process independently, and the value of 1 means the elementary cycles share the process. For example, if topology parameter for heating process is

$[1\ 1\ 0;\ 0\ 1\ 1]$

that means there are three elementary cycles for this ORC configuration, and elementary cycle 1 and 2, as well as 2 and 3, share the heating process, while elementary cycle 1 and 3 carry out the process independently. For the configuration in Fig.2, codification list for its topology parameter is

A: [0,0]
B: [1,1]
C: [0,0]
D: [0,0]

3. *ALGORITHM FOR INTELLIGENT SIMULTANEOUS CONSTRUCTION*

Section 2 clarifies the codification of ORC cycle, and this section will illustrate the algorithm and framework of intelligent construction with fluid selection. In previous researches, the evolutionary algorithm which belongs to computational intelligence has shown its practicability in intelligent construction. Thus, evolutionary algorithm is also adapted in this paper.

The hypotheses for this algorithm are as follow:

1. Working fluids for all elementary cycles are the same and there is no working fluid leakage;
2. Elementary cycle consists of four thermodynamic processes: heating process, cooling process, expansion process and compression process; heating process and cooling process are in the condition of constant pressure;
3. All the cycles happen in subcritical condition;
4. The mixture of working fluids of different elementary cycles is at the same temperature;
5. Heat loss except the one in heat exchangers is negligible.

3.1 Modifying rules

Due to the intrinsic randomness in evolutionary algorithm, there may be some conflictions between design and topology parameter, which needs to be modified.

In terms of heating and cooling process, if the requirement of topology parameter that elementary cycles share the processes, which means evaporation or condensation pressure of the elementary cycles should be equal, does not conform to the requirement of design parameter that value of pressure is different, then in this case, topology parameter has the priority and design parameter is modified correspondingly. At the same heat source condition, higher evaporation pressure or lower condensation pressure would generate more power output according to Carnot theorem. Therefore, if the confliction happens for heating process, initial pressure of expansion is revised to the maximum among them; and for cooling process, initial pressure of compression of the sharing elementary cycles is revised to the minimum among them for the same reason.

In terms of compression and expansion process, if the requirement of topology parameter that elementary cycles share the processes, which means pressure ranges of compression and expansion should intersect respectively, does not conform to the requirement of design parameter that the pressure ranges are nonoverlapping, then in this case, design parameter has the priority and topology parameter is modified correspondingly. The pressure range of compression and expansion do not intersect, meaning those elementary cycles cannot share compression and expansion process, so the binary variables of topology parameter are ought to be revised from 1 to 0. By doing this correction, elementary cycles with non-intersecting pressure range avoid sharing the compression and expansion process.

3.2 Algorithm framework

The simultaneous algorithm for achieving intelligent construction of ORC configuration and fluid selection has a nested three-level framework and is realized through MATLAB, employing evolutionary algorithm, SQP and 0-1 programming. The framework of the algorithm is shown in Fig.3. As depicted in Fig.3, the nested three-level framework includes upper-level, lower-level and outer-level algorithm.

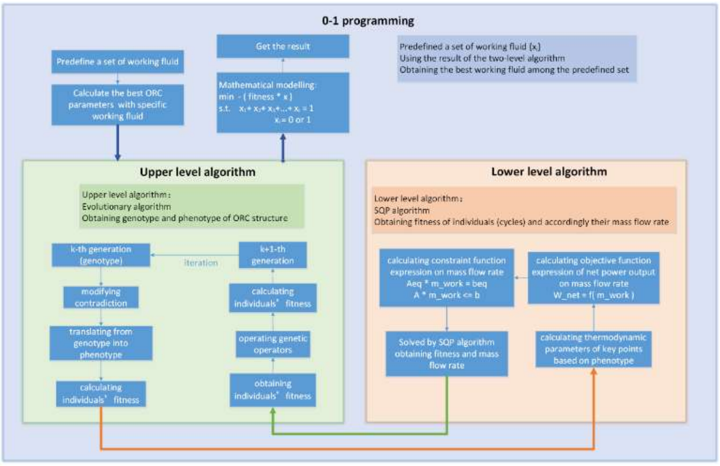


Fig.3 Algorithm framework

The upper-level algorithm adopts evolutionary algorithm, and, through codificaiton of design parameter and topology parameter, obtains genotype and phenotype of ORC structure that are passed to the lower-level algorithm. The genotypes of ORC structure, consisting of design parameter and topology parameter, are operated by genetic operators including selection operator, crossover operator and mutational operator. Selection operator is used to select individuals (potential solutions) with better fitness, namely higher net power output. The selection operator in this algorithm is tournament selection operator, which based on the value of individuals' fitness. Crossover probability is set to 0.5. Crossover operator for design parameter is arithmetic crossover, while single-point crossover is adopted for topology parameter. Mutational probability is set to 0.2. Mutational operator consists of four sub-operators, which can achieve the following function: (1) alter one of the design parameters for one of the elementary cycles; (2) alter the number of elementary cycles in one of the thermodynamic process, namely adding or deleting an elementary cycle from the specific process by topology parameter; (3) alter the number of sharing process, namely adding or deleting a thermodynamic process that is sharing by elementary cycles by topology parameter; (4) alter the number of elementary cycles for ORC structure, namely adding or deleting an elementary cycle from ORC. The fitness function for individuals is set to be net power output, which is related to the working fluid used in ORC and the structure of ORC under the known heat source conditions. The value of fitness for each individual is evaluated by transforming genotype into phenotype and then passing it to lower-level algorithm to calculate.

The lower-level algorithm adopts SQP to calculate the optimum fitness of each individual that are returned to the upper level algorithm, based on the state properties in REFPROP version 9.1. Fitness function, which is net power output, is related to thermodynamic parameters and is irrelevant to economy, and depends on the boundary conditions of each thermal cut. For a specific structure defined by design and topology parameter with specific working fluid, only mass flow rate is variable. Thus, the SQP takes mass flow rate as an only variable. The constraints that must be satisfied are about heat transfer feasibility in the "black-box", for example, the minimum heat transfer temperature difference must be above pinch point and the total heat release by heat flux must be larger than the total heat absorption by cold flow.

The outer-level algorithm adopts 0-1 programming, using the results of net power output from the two-level algorithm. It introduces working fluid selection coefficient x_i. Each working fluid selection coefficient represents every fluid candidate in a predefined set of working fluids, and equals to 0 or 1, whose sum equals to 1. The value of 1 means this kind of fluid is selected and value of 0 means this kind of fluid is not selected. The objective function of 0-1 programming is maximum value of the sum of net power output for all fluid candidates. Through the nested three-level algorithm, intelligent construction of ORC configuration and fluid selection are achieved simultaneously.

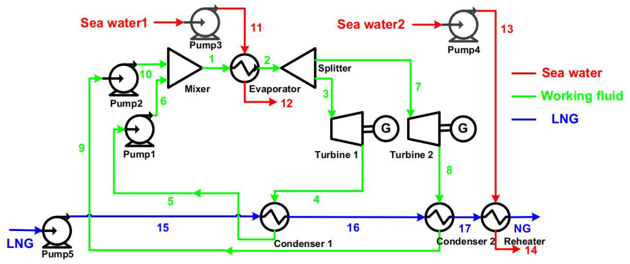
4. RESULTS AND DISCUSSION

4.1 Accuracy verification

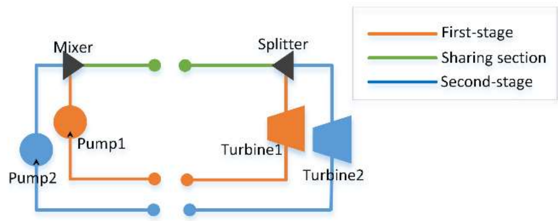
The accuracy of the algorithm is verified by the reference data of a two-stage condensation ORC system (TCRC) with propane as working fluid to recovery cold energy of 3600 kg/h of liquefied natural gas (LNG)[7]. The heat source used in the reference is sea water, with inlet temperature of 288.15 K and outlet temperature of 283.15 K. Adiabatic efficiency of both pump and turbine is 80%. Minimum approach temperature in heat exchangers is set to be 5 K. Fig.4 depicts schematic diagram and simplification form of the TCRC system, which shows it is divided into two elementary cycle. Other operation parameters of the TCRC system and expression of topology parameters for the simplified TCRC system are listed in Table 2. The TCRC system is simulated using Aspen Hysys software and the maximum net power output is $1.1576{*}10^5$ W.

Because the purpose of the reference is to utilize the cold energy of LNG with certain amount, the verification is done under the fixed heat absorption of LNG. Therefore, by fixing the above parameters including working fluid, inlet and outlet temperature of heat source, adiabatic efficiency of pump and turbine, minimum approach temperature in heat exchangers and topology parameters, as well as by confining thermodynamic parameters to subcritical state, the accuracy of the algorithm is verified through simulation in MATLAB.

Calculation result for net power output of the algorithm is $1.1366{*}10^5$ W, with relative error of 1.81% compared with $1.1576{*}10^5$ W of the reference, which shows the accuracy and practicability of the nested algorithm.



(a)



(b)

Fig.4 Schematic diagram and simplification result of TCRC

Table 2 Operation parameters of TCRC

Parameters	Value			
Net power output	$1.1576{*}10^5$ W			
Topology parameter	Compression process	Heating process	Expansion process	Cooling process
	[0,0]	[1,1]	[0,0]	[0,0]
Design parameter	First-stage		Second-stage	
	T (K)	P (kPa)	T (K)	P (kPa)

Initial state of compression		174.76	3.323	231.56	103.7
Initial state of expansion		284.15	654.81	284.15	654.81
Mass flow rate (kg/s)	Working fluid		Heat source	Cold source	
	First-stage	0.4067	30.27	1	
	Second-stage	0.8014			

4.2 *Case study*

Based on the above TCRC system, predefining a set of 13 organic fluid shown in Table 3, the algorithm is employed to realize simultaneous optimization of working fluid and corresponding structure of cycle. The heat absorption of LNG is still fixed, and the inlet and outlet temperature of heat source, minimum approach temperature in heat exchangers and adiabatic efficiency of pump and turbine are the same as the reference data. The above parameters determine the boundary conditions for case study. Thermodynamic parameters are subcritical as well. By the algorithm for intelligent construction of configuration and fluid selection, topology parameter, design parameter and working fluid are optimized to achieve maximum net power output of ORC with the determined boundary conditions.

The best net power output for each fluid candidate is shown in Fig.5, and obviously, R170 owns the highest value. The results are summarized in Table 4. Topology parameter of structure corresponding to R170 shows there are two elementary cycles sharing expansion and cooling process. Diagram of the structure is shown in Fig.6. Compared to the parameters of cycle with propane, the reason that TCRC generates more net power output lies in lower condensation temperature. It can be seen that evaporation temperature changes little, but condensation temperature for R170 is about 140 K, lower than that about 174 K for propane. This contributes to larger figure area in T-s or P-h diagram, representing the potential to generate more net power output.

Table 3 Organic fluid candidates

Organic fluid	R23	R32	R41	R125	R134a	R143a
R150	R152a	R170	R116	R290	R218	R600

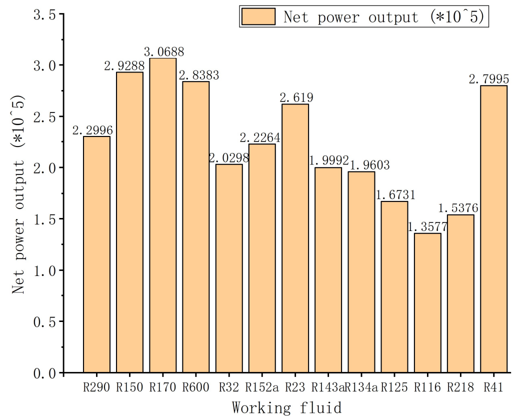


Fig.5 Results of net power output for fluid candidates

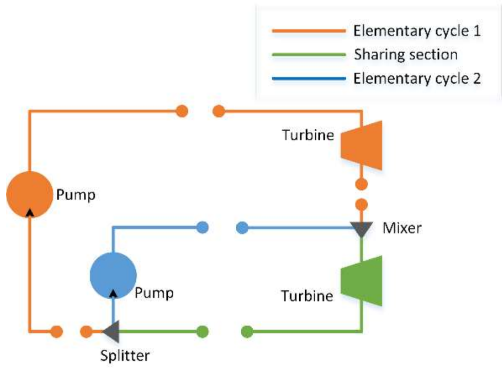


Fig.6 Structure corresponding to topology parameter

Table 4 Parameters of optimum fluid and TCRC structure

Parameters		Value		
Optimum fluid		R170		
Net power output		$3.0688*10^5$ W		
Topology parameter	Compression process	Heating process	Expansion process	Cooling process
	[0,0]	[0,0]	[1,1]	[1,1]
Design parameter	Elementary cycle 1		Elementary cycle 2	
	T (K)	P (kPa)	T (K)	P (kPa)
Initial state of compression	141.92	9.781	149.55	9.781
Initial state of expansion	284.09	3001.7	281.72	2854.1
Mass flow rate (kg/s)	Working fluid		Heat source	Cold source
	Elementary cycle 1	0.4012	35.43	1
	Elementary cycle 2	0.6422		

5. CONCLUSIONS

A nested three-level algorithm, employing evolutionary algorithm, SQP and 0-1 programming, is proposed to simultaneously achieve fluid selection and intelligent construction for ORC configuration. Based on HEATSEP method, an ORC can be described through design parameter and topology parameter, where design parameter contains thermodynamic state parameters and topology parameter reveals the structure features of ORC. Encoding design parameter with real number coding and topology parameter with binary coding and taking net power output as objective function, the genotype and phenotype of ORC structure is generated by evolutionary algorithm and SQP. 0-1 programming employed in the outer level introduces working fluid selection coefficient to screen organic fluids.

Through simulation using reference data of a TCRC system with MATLAB and REFPROP, relative error of the net power output is 1.81%, showing the accuracy of the nested algorithm. With a case study of a predefined set of 13 organic fluids, optimum working fluid and its corresponding structure for the TCRC system are found. Results show that not only can the proposed algorithm achieve intelligent construction for ORC structure, but also select optimum pure organic fluid in terms of maximum net power output.

Since zeotropic mixtures have an advantage on improving ORC performance and the cost factor of heat transfer network is usually taken into consideration in actually application, one of the tasks for future work is the selection of zeotropic mixtures, and another is the synthesis for specific structure of heat transfer network.

ACKNOWLEDGEMENT

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