GEOMETRIC OPTIMISATION OF GROOVED HEAT PIPES BY A GENETIC ALGORITHM TECHNIQUE

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Abstract

In this paper, a genetic algorithm is used to perform a grooved heat pipe optimisation. First, we briefly describe the method and we justify its choice. Then the advantages as the suitability to find the global optima or the management of discontinuous and discrete variables are underlined. We also discuss the multi-objective problem treatment by the Pareto front technique. We apply the genetic algorithm to find the heat pipes offering both the maximum heat transport capacity and the minimal external envelope diameter. As genetic algorithm is used, numerous calls to the objective function are required. Therefore, a fast model based on a semi-analytical hydraulic approach is developed to estimate these objectives. It calculates the maximal heat transport capacity of the heat pipes independently of the external working conditions. The Pareto front is discussed and illustrated with two geometries. We analyse the results in term of friction losses and capillary pumping action.

KEYWORDS

Grooved heat pipe, Capillary pressure, Friction losses, Genetic algorithm, Optimisation

INTRODUCTION

Since a couple of decades, the heat pipe technology has proven its efficiency in the thermal control of highly dissipative equipments such as electronic components of satellites. As microgravity experiments are rare and expensive, many industries active in the space domain show an interest to develop numerical tools allowing the sizing, the characterisation and the risk failure prediction of the heat pipes.

A conventional heat pipe is a closed thermodynamic system in which a liquid (ammonia, water, ...) evaporates in the vicinity of a dissipative source and condenses in contact with a cold region. To ensure its passive working in a microgravity environment, the heat pipe is composed of a vapour duct surrounded by a capillary structure. This structure allows for the fluid to return from the cold zone to the heat source. As most of the energy is converted during the phase change, the thermal performances of heat pipes are considered as being at least one hundred times higher than the copper ones.

Among conventional heat pipes, grooved heat pipes are often used for spacecraft thermal regulation as they offer a high capillary pumping action, allowing for an easy motion of the fluid between the radiative panels and the dissipative components of the central unit. As power increase and size reduction are constantly asked in the space industry, geometric optimisation of the designed product appears as a real challenge for industrials involved with this technology.

As in most of the industrial optimisation cases, grooved heat pipe optimisation is not an easy matter. It appears as a multi-objective problem strongly constrained by physical and manufacturing limitations among others. Moreover, the objectives are often contradictory increasing the complexity to find a unique solution. The multi-objective optimisation aims to determine the set of results offering the best compromise between the different objectives.

The paper is organised as follows. We first introduce the genetic algorithm technique and we argue the choice of this optimisation model. Then, we explain the model we developed in order to estimate the heat pipe objectives we want to optimise and, finally, we discuss the results obtained from this optimisation.

THE GENETIC ALGORITHM

Principle

The choice of the optimisation algorithm strongly depends on the application for which it is implemented. In this paper the so-called genetic algorithm (GA) optimisation technique is employed because it is able to deal with multi-objective and constrained problems [1]. Moreover, thanks to the fast heat pipe evaluation method employed in this research, the large number of function evaluations usually required by the GA is not a limitation.

Genetic algorithms were designed by Holland in the 70 s, and improved and made well known by Goldberg in the 80s [2]. GAs are becoming more and more widely used in mechanical and aerodynamic problems, including preliminary design of turbines, aerodynamic optimisation using CFD, multi-objective optimisation of turbomachinery blades [3]. More recently, GAs used with meta-models have proven to provide very powerful optimisers able to tackle multi-objective and multi-disciplinary optimisation of three-dimensional shapes [4].

Genetic algorithms mimic natural behaviour in terms of biological evolution in order to reach the best possible solution to a given problem. Weak individuals tend to die before reproducing, while the stronger ones live longer and generate new off-springs who often inherent the qualities that enabled their parents to survive.

A GA is summarized as follows. An initial population is generated by randomly selecting individuals (heat pipe) parameters in the whole design space. Then pairs of individuals are selected from this population based on their objective function values. The performance of an individual is measure by its fitness. Then, each pair of individuals undergoes a reproduction process to generate a new population in such a way that fitter individuals will spread their genes with higher probability. It relies on the *crossing* of the genes (heat-pipe parameters) by different techniques and a *mutation* process in order to ensure a good variety among the individuals. The children replace their parents. As this proceeds, inferior traits in the pool die due to lack of reproduction. At the same time, strong traits tend to combine with other strong traits to produce children who perform better.

The basic scheme of a typical genetic algorithm is summarised in Fig. 1.

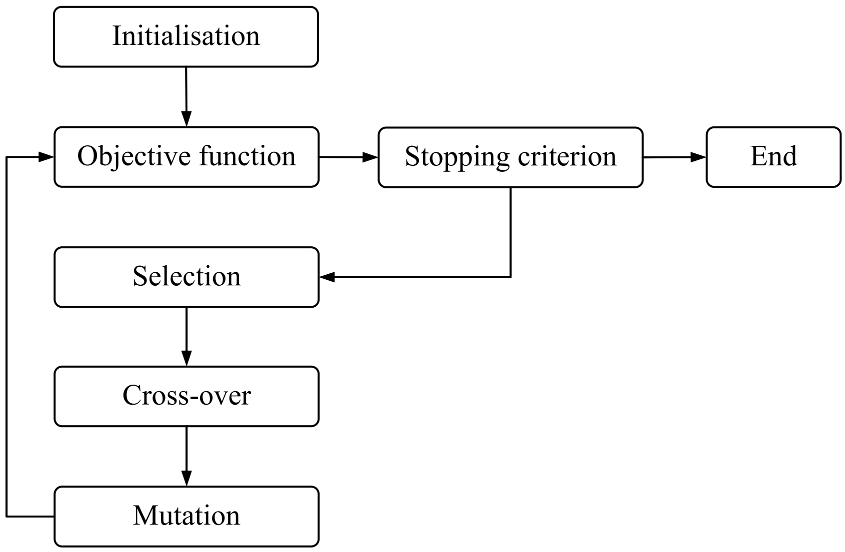

Fig. 1. Iterative scheme of a genetic algorithm

However, dealing with only one objective is not sufficient in this application and therefore multi-objective evolutionary algorithms (MOEA) have been developed in order to find the Pareto optimal set of individuals. The Pareto front is the set of nondominated solutions such that there exists no other feasible individuals in the search space better with respect to all criteria simultaneously. One of the most widespread MOEA is the Strength Pareto Evolutionary Algorithm-2 (SPEA-2) – proposed by Zitzler and Thiele [5], which stores the best (nondominated) points in an external archive during the search process.

Defining a *stopping criterion* is not straightforward in a multi-objective problem. Again, different techniques exist; but in this research a fixed number fo generation cycles has been used instead of a stopping criterion.

Advantages for the grooved heat pipe optimisation

The choice of the GA optimisation technique essentially relies on four considerations.

First, the large variety of parameters in the design space may induce the presence of local optima that the optimisation technique must be able to avoid. Therefore, the classical gradient-based algorithms may be not appropriated. At the opposite, stochastic approaches, such as a GA technique, do not encounter this problem and are therefore more suitable for the determination of the global optimum.

On the other hand, GAs require a large number of the objective function evaluations to reach a good convergence level. This is usually a drawback for applying the genetic algorithm alone in a real life design problem. However, in this case, the code allows for a fast estimation of the performances (as described in the following question) and consequently the optimisation process can be achieved in a reasonable time.

Then, the heat pipe optimisation requires the definition of several conflicting objectives which usually relies on a GA. This is the case of the Pareto front technique we used in this work. Solutions located on the Pareto front are optimal in the sense that no other solutions in the design space are superior to them when all the objectives are considered.

Finally, the genetic algorithm usually allows using integer discrete design variables. This is a very useful advantage of the genetic algorithm in the studied case as the number of grooves is a critical design variable.

THE GROOVED HEAT PIPE MODELLING APPROACH

The heat pipe performances are estimated by a one-dimensional semi-analytical hydraulic model.

The code relies on the equilibrium between the friction losses induced by the liquid and the vapour motions and the capillary pressure developed in the grooves. The convergence criterion imposed to calculate the maximum heat transport capacity assumes the maximum capillary pressure is reached at the end of the evaporator section. In that case, any power increase would lead to the dry out of the grooves and the working failure [6].

Capillary pressure is described by the Young Laplace equation with the assumption of an infinite curvature radius in the axial direction. Friction losses are defined by one dimensional correlations based on a fully-developed flow [7-11]. Laminar regime is considered in the liquid phase and both laminar and turbulent regimes are supposed for the vapour flow. The code also considers a shear stress at the liquid/vapour interface due to the counter flow of the liquid and the vapour. Most of the one-dimensional heat pipe models use correlation formula established in the literature for circular closed channels. They define an equivalent diameter in order to take into account their specific geometry. Nevertheless, it can be demonstrated this leads to errors that we cannot neglect. In order to improve the friction loss estimate inside of the grooves, we have implemented a method allowing for the estimate of the friction losses for any kind of duct shapes, opened or not [6, 12].

The code execution is fast (no more than 2 minutes) and the result only depends on the geometric parameters of the heat pipes (no influence of the external conditions). It is therefore suitable for a geometric optimisation and for the genetic algorithm use as it requires an important number of calls to the objective function.

RESULTS

Case description

A large number of parameters is necessary to define the grooved heat pipes. These are either continuous or discrete.

First of all, grooves are described by a slot height (h), an opening at the bottom and the top of the slot (w_b, w_t) and a hydraulic diameter (Φ_h), specific to re-entrant channels. Fig. 2 illustrates these parameters.

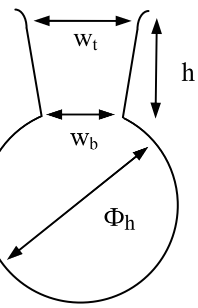

Fig. 2. Re-entrant groove design parameters: one defines the slot height (h), the bottom and the top slot widths (w_b, w_t) and the hydraulic diameter (Φ_h)

Afterwards, other design variables must be imposed such as the vapour internal diameter and the number of grooves (discrete parameter).

All these design variables were considered as optimisation parameters. The design intervals, normalised by the maximum external envelope diameter Φ_{max} (see below), are [0.1, 0.95] for the internal diameter and [$5\cdot10^{-3}$, 0.3] for the hydraulic diameter, the slot widths and height. The absolute [1, 30] interval was chosen for the groove number.

The large variety of parameters and the related constraints are the main difficulties the genetic algorithm has to cope with. Indeed, eighty per cent of the initial generated heat pipes were rejected. It forces the algorithm to make lots of objective function calls in order to generate a representative initial population.

The first constraint type comes from the intrinsic link between the geometric parameters. For example, it is impossible to connect the slot and the hydraulic diameter if the diameter is lower than the bottom slot width.

On another hand, we must impose a minimum distance between two adjacent grooves in order to respect the building limitation (d_{min}). One imposes it to 0.04 in reduced unit.

Finally, experiments have revealed the necessity to impose a maximum ratio between the hydraulic diameter and the minimum slot width (ρ_{max}). This is for allowing the escape of a vapour bubble appearing in the groove bottom in boiling conditions.

The objectives were contradictory and constrained. They are the power maximisation (with a minimum power to reach Q_{min}) and the external envelope diameter minimisation (with a maximum value to reach Φ_{max}). Nevertheless, constraints were treated a posteriori in this study in order to show a wider Pareto front. Note that the external diameter includes a minimum value of the solid thickness between the groove bottom and the heat pipe outside (g_{min}).

Calculations were performed in microgravity for a working temperature of 75 degrees and ammonia fluid introduced at 20 degrees. The liquid volume introduced corresponds to the free volume in the grooves. The lengths of the evaporator, the condenser and the adiabatic zone were imposed to a fixed value of 15.79, 5.26, and 89.47 in reduced units.

A population of 200 individuals and 200 reproduction cycles were used in this study. As a consequence 40 000 heat pipes have been evaluated.

Result discussion

Once the convergence of the genetic algorithm is reached, we obtained the Pareto front (see Fig. 3). Objectives are proposed in reduced units in relation with the constraints. The power is divided by Q_{min} and the external diameter is divided by Φ_{max}. Individuals respecting the constraints are therefore the ones included in the shaded area.

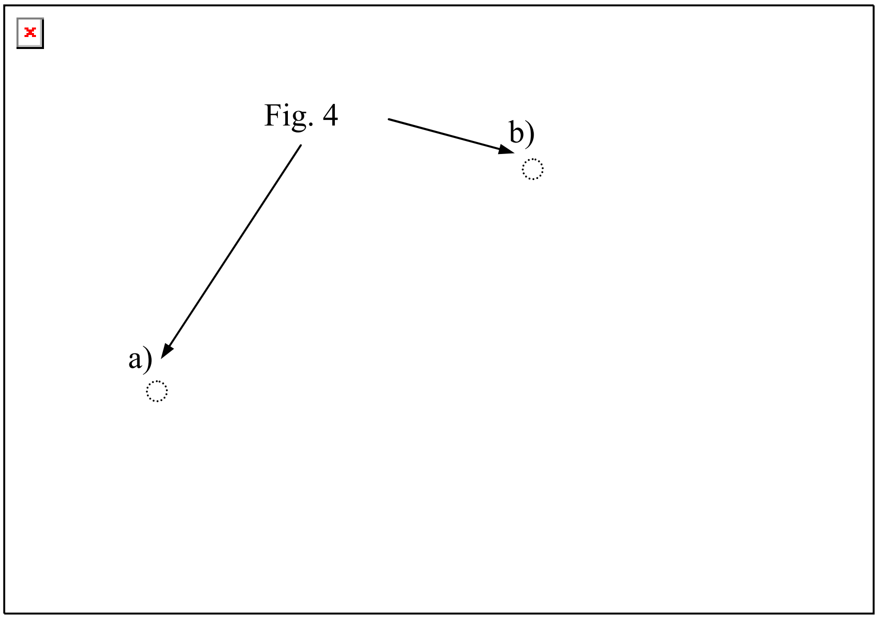

Fig. 3. Pareto front resulting of the grooved heat pipe optimisation with two constrained objectives: the maximisation of the power and the minimisation of the external envelope diameter. Individuals respecting the constraints are located in the shaded area

The Pareto solution shows the individuals which cannot be dominated by another individual in term of both objectives simultaneously. It corresponds to the best compromise between the two contradictory objectives we imposed. The selection of one individual on the front depends of the industrial application and objectives. Fig. 4 illustrates the heat pipe profile of two solutions (see the labels a) and b) showed by the arrows in Fig. 3).

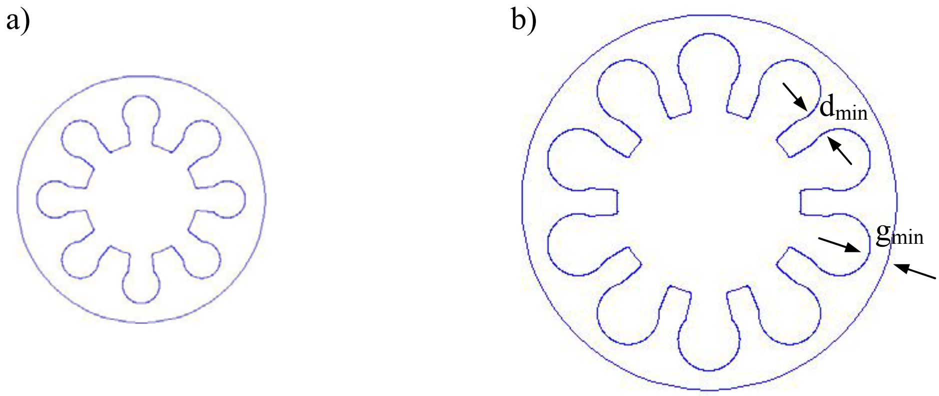

Fig. 4. Cross sections of two optimised heat pipes issued from the Pareto front of Fig. 3 (see labels *a)* and *b)* on the Fig. 3). The heat pipe on the right satisfy the constraints imposed both on the design variables and on the objectives while the heat pipe on the left does not satisfy the power constraint. The minimum thickness between two grooves d_{min} is reached and we showed the minimum distance between the groove bottom and the outside of the pipe, g_{min}

Different characteristics, common to all individuals in the front, can be extracted from those examples.

In a general way, the genetic algorithm tried to increase the size of the hydraulic diameter and to enlarge the internal diameter. This is a direct consequence of the fact that friction losses are lower in larger ducts, increasing the transport capacity. Nevertheless, this diameter increase is limited by the second objective, the minimisation of the external diameter. As, in most cases, the liquid losses are higher than the vapour ones, the main increase is performed on the hydraulic diameter parameter.

Nevertheless, the enlarging of the hydraulic diameter, which is combined with a slot opening by the way of the constraints ρ_{max}, is responsible for the decrease of the capillary pumping pressure, reducing the heat transport capacity. Note that the ratio between the hydraulic diameter and the minimum slot width opening reaches ρ_{max}. A compromise is not straightforward as the parameters are strongly coupled in the performance determination. This justifies the use of an optimisation methodology, able to manage a large space of design variables in the same time.

Note that the genetic algorithm selected individuals with a top width slightly smaller than the bottom width. In the same time that it tried to reduce the friction losses, the genetic algorithm maximised the capillary pressure (essentially developed in the slot) by choosing this kind of configuration.

Finally, the genetic algorithm reduced the space between two adjacent grooves to the minimum value imposed by the constraint (d_{min}) (see Fig.4). This is a consequence of the assumption we did on the volume of fluid. We decided to impose a liquid volume equivalent to the free volume inside of the grooves. The more the grooves are closer and large, the more the volume of fluid is important and, finally, the more the transport capacity increase. Then, a large power cannot be reached with a small groove number as shown in Fig. 5.

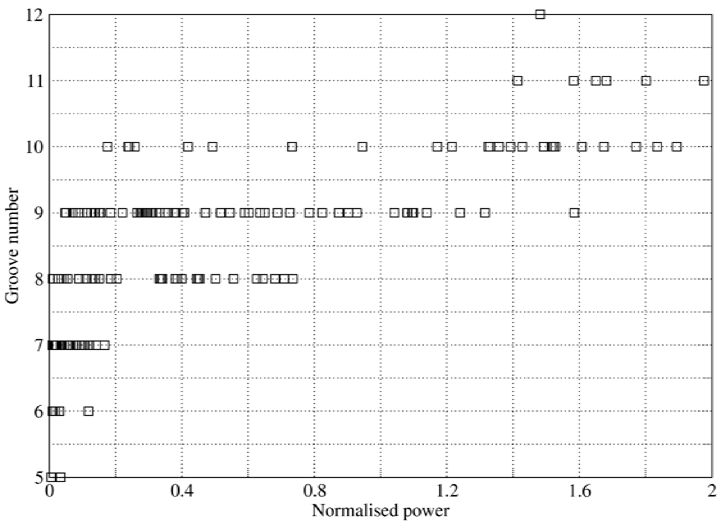

Fig. 5. Groove number distribution according to the power for Pareto front individuals. The minimum number of grooves increases with the power objective

CONCLUSION

In this paper, we have chosen a genetic algorithm to optimise the grooved heat pipe performances. We discussed the basic principles of the method and justified this choice by different considerations such as the multi-objective character of the optimisation case, and the nature of the design variables (continuous and discrete ones). Genetic algorithms require an important number of calls to the objective function. Therefore, a fast and accurate one-dimensional hydraulic model was implemented. This is able to predict the heat pipe maximum heat transport capacity. As the result does not depend on the external conditions, the code appears suitable for geometric optimisation. An optimisation case was proposed. It was based on two contradictory objectives (the maximisation of the power and the minimisation of the external pipe diameter) and several objectives and constraints. Pareto front was discussed and two individuals of the front were used to explain how the algorithm tried to reduce the friction losses and to enhance the capillary pumping action in the same time, respecting the design constraints. Proportional relation between the number of grooves, or the liquid volume, and the transport capacity was also highlighted.

Acknowledgments

The first two authors acknowledge the support by the Walloon Region and the European funds ERDF and ESF under contract N°EP1A122030000102.

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