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Development of an expert system based on fuzzy logic as support for heat pipes design

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ABSTRACT

Heat pipe design and selection require specialist knowledge due to numerous possible combinations and restrictions that should be taken into account. The general objective of this work is to design a Specialist System that assists future engineers in material and working fluid selection for a suitable heat pipe application, based on the technical operating requirements. The methodology consisted of a qualitative perspective through interviews with two specialist engineers in the heat pipes area. The resulting information from the interviews was organized into a library, working as a source for the specialist system. In addition, several books from the literature completed the information in the library. Based on the operating conditions and the provided library, the program recommends suitable materials and working fluids and the necessity of porous media for the application, similar to a consult with a heat pipe specialist. The new expert system can be a tool for researchers and engineers in heat pipe design as passive control systems, providing more suitable solutions for each application.

Keywords: Expert Systems, Fuzzy logic, Heat pipes, Selection

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1. Introduction

The necessity for energy consumption reduction, increase in the efficiency of industrial processes, and thermal control of electronic equipment have been promoted the development and improvement of a wide variety of devices able to transfer high heat transfer rates, e.g., compact and two-phase heat exchangers. Passive heat transfer devices that use the phase change phenomenon, such as heat pipes and thermosyphons, have gained relevant space in such tasks due to their reliability, high thermal performance, size, weight, and cost.

A heat pipe is a passive heat transfer device that transports energy between a hot side, known as the evaporator section, and a cold side, called the condenser section, using the change from liquid to vapor of a working fluid. The state of the art involving heat pipes is in constant growth. Several companies and laboratories are dedicated to the heat pipe research, concerning the improvement of their fabrication techniques, thermal performance, and operation. However, the application of heat pipes in the Colombian national industry is limited, due to a lack of knowledge about these devices by the engineers that are responsible for the design and manufacture of heat exchangers. When heat pipe applications are developed by non-specialists in the field, the results can be inefficient designs and unsuitable heat exchangers, which yield unsuccessful results and, therefore, hinder the expansion of this technology in industrial process applications.

Thus, the selection of each component according to an unlimited number of options, compatibility, resistance, advantages, and disadvantages, other factors, should be taken into account by engineers and designers of heat pipe-based heat exchangers. Based on that, numerous possible combinations become necessary to understand, following some professional criteria or information from specialized literature, which often conflicts between different sources of knowledge. In this regard, heat pipe selection is a task that requires specialist knowledge, as several types of heat pipes can be suitable for the same application. Even if the heat pipe is correct from a technical point of view, the results can be high costs or problems during the implementation, which can be avoided with a proper design. Therefore, the Expert System (ES) is a solution to help companies without experience or experts in the field but aim the heat pipe application.

The Expert System has been functionalized since the 1970s and is widely studied nowadays [1]. According to [2], this system was developed to solve unsolvable problems or issues in which expert knowledge was essential, using programming or mathematical techniques. The computer stores the required data, so people can access the information when necessary [3]. Even so, the model helps to make inferences and get specific conclusions, which should be explained and supported by a specialist, i.e., the tool is not able to replace the expert [4]. Specialized language (LISP, PROLOG, and CLIPS) and algorithmic language are the languages commonly used (C or Pascal) [2].

The Fuzzy Expert System (FES) is one of the variations of the Expert System. In this version, a mathematical model can address the uncertainty problem, became the system unique in this function and the most reported in the literature [6]. The main element of FES is fuzzy logic [7], which is a nonlinear mapping of an input data vector into a scalar output [8]. According to [7], fuzzy logic is basically an interface between humans and computers. People are able to understand, analyze, and decide based on ambiguous data, while computers can take just binary data, i.e., they accept only two possible states, such as 1 or 0, and ‘true’ or ‘false’. Therefore, fuzzy logic facilitates the treatment of this complex information considering the problem uncertainties.

Despite being a well-known tool, the Expert System has been used as a research tool in plenty of areas. For instance, the authors of [6] evaluated the benefits and issues of Expert Systems for medical applications. [9] discussed the importance of this specific tool in human disease diagnostics. In this line, [10] studied the diagnosis of diverse types of cancer using the FES. Also, several researchers applied the Expert System in recognition of hypothyroidism [11], child anemia [12], depression [13], and Uveitis [14]. In the engineering area, [15] investigated the ES implementation for the selection of suitable hyperparameter optimization techniques for manufacturing. Another example of ES implementation is for fire safety analysis in the nuclear area performed by [16], which concluded that the Expert System is useful in such applications because it allows quick identification of the configurations at risk of an installation. Moreover, [17] applied the ES for dam safety management of a hydropower station.

Concerning ES implementation in engineering design applications, [18] developed a system to help in the selection of design for environment methods and tools. The authors concluded that the ES provides practical solutions to complex problems in an initial stage and could be expanded. [19] applied the ES tool in the arrangement design of a submarine compared to other devices in operation but concluded that the system could be improved for more realistic problems. [20] studied an Expert System for a submarine arrangement design, considering the high dependence on the previous submarine projects' data and specialists' knowledge. [21] built an ES to develop a simulation model for the metal substructures casting for metal-ceramic crowns. The authors accomplished that the CAD/CAR feature parameters and further modifications can be controlled, besides being able to prepare the CAD model. Based on the recent research involving the Expert System, the ES tool can be applied to any problem requiring a quick decision, monitoring, or analysis of data, as in the detection of nonconformity. Heat pipe design is very similar to the problem presented by [19] [20], in which the knowledge of a specialist acquired in decades of research is required. In this regard, a robust ES allows the aggregation of plenty of knowledge of heat pipe arrangements, which are inserted and evaluated, when necessary, and can be added to the collection for the next project. In this context, the objective of this work is to implement a specialist system for performing the selection of fluids, shell materials, and the necessity for porous media according to the requirements of the operating conditions.

2. Materials and method

The method consisted of three steps: knowledge sources and acquisition, knowledge representation, and inference method. The present work adopted the CLIPS, a widely used expert system tool developed by NASA-Johnson Space Center, written using C language [2], [5].

2.1. Sources of knowledge and acquisition of knowledge

Heat pipes consist of a multidisciplinary development involving different areas: materials, porous media, working fluids, and experimental research of heat pipes, which are hard to find in specialized literature. Therefore, the knowledge acquisition for selecting the heat pipe components will be carried out with two specialists. The first one has been developing materials for heat applications since 2010, and the second one has studied different heat pipes. The specialists collaborated in the present work by providing their knowledge in surveys and personal interviews. In addition, the present study was based on several books found in the literature, such as [22] and [23]. The most important feature of designing a heat pipe, which depends only o the research's knowledge, is the selection of components, materials, and manufacturing procedures. These features are in continuous development; therefore, an algorithmic approach can be hindered due to the excess of information. Contact to the specialist must be accomplished to select the heat pipe, e.g., providing him information about the application of the heat transfer device as: available space for the installation, position, operating temperatures, and the environmental conditions. In the sequence, the specialist defines the type of heat pipe, characteristics of the components, and the working fluid. Besides that, the explication of the selected heat pipe is included. This system is justifiable due to the expertise of the specialist concerning heat transfer devices. The verification method will be manual. The heat pipe case and the porous media material might be different. However, in the first version of the algorithmic, they will consist of the same material. Future versions improvement will consist of various heat pipes, considering the operating limits. The inputs and outputs of the system presented in Tables 1, 2, 3, 4, and 5 were defined as initial parameters to create a prototype in CLIPS based on information and data from the specialist's knowledge.

Table 1. Input data

Heat flux q” [W/m^2]
Security level
Weight
Relative position evaporator-condenser
Operating temperature range
Environment of heat source and sink

Table 2. Output data

HEAT PIPE	Porous media	- Yes - No
	Porous media and shell material	- Copper - Stainless Steel - Aluminum
	Working fluid	- Water - Methanol - Ammonia - Sodium - Acetone

Table 3. Material properties

Material	Corrosion resistance	Density [kg/m³]
Copper	Low	8930
Aluminum	Low	2700
Stainless Steel	High	7850

Table 4. Material compatibility

Material	Compatibility	Incompatible
Water	Stainless Steel, Copper	Aluminum
Ammonia	Aluminum, Stainless Steel	Copper
Methanol	Stainless Steel, Copper	Aluminum
Acetone	Stainless Steel, Copper, Aluminum	-
Sodium	Stainless Steel	-

Table 5. Working fluid properties

Working fluids	T_{min} [K]	T_{max} [K]	q''_{crit} [W/cm²]	Toxicity
Water	303	473	100000	No
Methanol	283	403	5000	Yes
Ammonia	213	373	12000	Yes
Sodium	873	1473	500000	Yes
Naphthalene	408	478	10000	Yes

2.2. Knowledge representation

The life cycle chosen for the knowledge implementation was the model of incrementing its functionality. It was applied functions and tested the coherence and quality of the results before implementing other functions. The knowledge was represented by the methodology of rules and facts, as well as semantic networks. The paper also presents a representation scale to recommend the best heat pipe within the possible options.

In the present, chaining forward was used for the development of the system, as this method is the most appropriate for the problem addressed. The knowledge representation follows three levels of hierarchy, which are presented in

Figure 1: level 1-Class; 2-Abstract Class and 3-Type class.

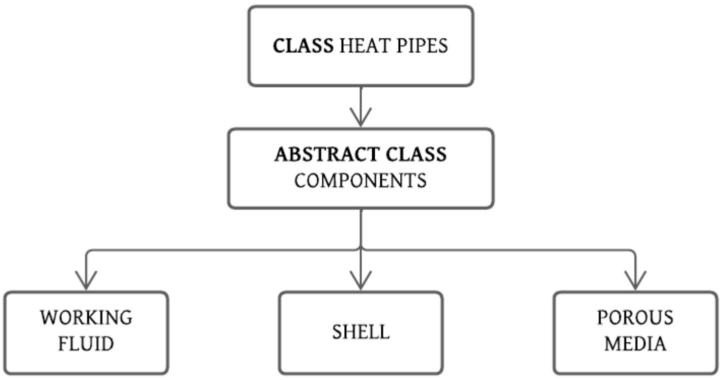

Figure 1. Hierarchy of knowledge representation

The hierarchy levels, presented

Figure 1, are described according to each category. The first one is the Class, Heat Pipe, defining the parameters used to design the heat pipe. These are obtained by questioning the user. The second level is the Abstract Class that involved the Components of a heat pipe. Finally, the third level is the Type Class, which is divided into three constituents:

Working fluid: It defines attributes to be considered, as many as critical heat flow, operating temperature range, and its toxicity.

Shell: It attributes the weight and corrosion resistance. In the next version, compatibility with the working fluid must be implemented, in addition to the maximum operating temperature.

Porous media: It was not determined, it was only defined whether the porous media is required or not, depending on the inclination or the specific application.

2.3. Operating rules

The main operating rules are listed as follows:
Temperature rules:

1. If $T_{operating}$ is greater than T_{min} of the working fluid and lower than T_{max}, the fluid is able to be the working fluid

Security rules

2. If the working fluid cannot be hazardous, the dangerous fluids are removed

3. If the working fluid can be hazardous, the dangerous fluids are not removed

Rules of environmental conditions:

4. If the pipe is subjected to a corrosive ambient, the heat pipe material must be corrosion resistant

Weight restriction rules:

5. If the weight relevance is low, the density of the material must be lower than 10000 kg/m^3

6. If the weight relevance is average, the density of the material must be lower than 5000 kg/m^3

7. If the weight relevance is high, the density of the material must be lower than 3000 kg/m^3

Rules of the relative position evaporator-condenser:

8. If the inclination of the heat pipe is horizontal, a porous media is needed

9. If the inclination of the heat pipe is vertical, the heat pipe does not need a porous media

10. If the inclination of the heat pipe is variable, a porous media is needed

11. If the heat pipe is not affected by gravity, a porous media is needed.

2.4. Inference method

The inference method implemented in the present work is direct chaining. The information is obtained by uploading questions in the program from the user, which is chained to recommend the working fluid-shell-porous media. The final answer is a list of the "best option" for the user's application. A scheme and uncertainty were also implemented as the first approximation in the prototype. The uncertainties were included because of the following reasons: lack of knowledge of the specialists about how the materials would behave in some operating conditions and limited information in the literature. Question threading is presented in Figure 2.

The uncertainties of the specialist system can come from diverse sources, being them due to the data (missing, unavailable, unreliable, ambiguous), conflicting measurements, inaccurate representation, assumptions, and modeled knowledge.

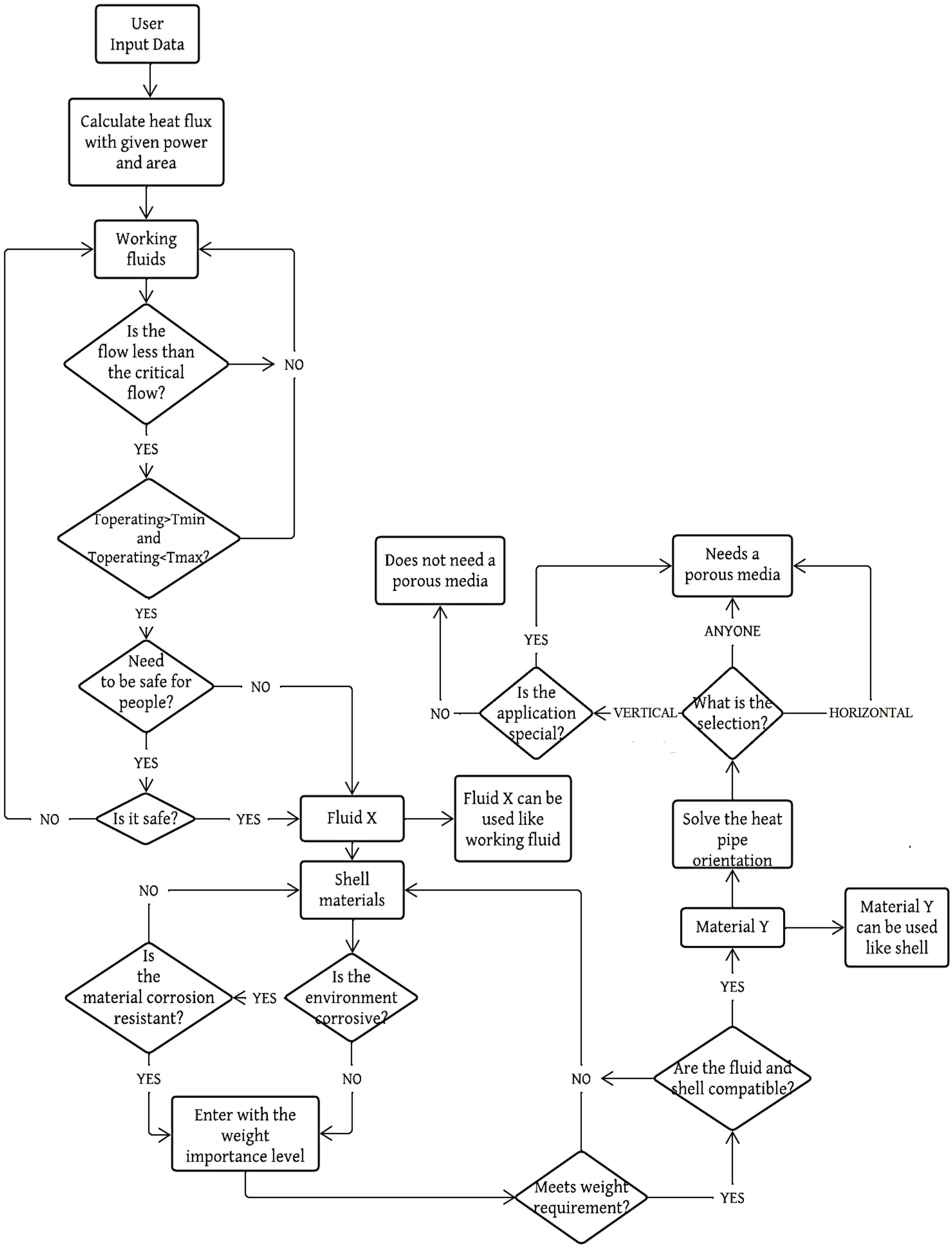

Figure 2. Question threading

3. Results

3.1. Verification and validation

Tests were performed for 100% of the possible combinations, ensuring the correspondence between the specification and the given results. Also, these tests evaluated semantic and syntax errors.

Specialists have in-depth knowledge of heat pipes in low-temperature applications that were used for the system validation associated with low dissipated heat loads. They validated the system by comparing the working fluids of the answer with those recommended by the literature.

In future versions, at least one specialist will be interviewed for the validation of high-temperature selections, in addition to the bibliographic sources, improving the data quality.

Figure 3 presents the first validation considering high heat flux, safe working fluid, high operating temperature, high mass density, corrosive environment, and horizontal operating position.

```
CLIPS> (RESET)
CLIPS> (RUN)
Is the heat flux high > 20 W/cm2, medium until 20 W/cm2 or light until 10 W/cm2? high
Must the fluid be safe/toxic yes, no, unknown? yes
Is the pipes Toperating range low (273K-400K), medium (400K-550K), high>550K, unknown? high
Is the weight importance low until 10000 kg/m3, medium until 6000 kg/m3, or high until 3000 kg/m3,
unknown? high
Is it works in corrosive environment yes, no, unknown? yes
Is the degree of corrosion resistance negligible, light, medium or high, unknown? medium
Does the pipe work horizontally, vertically or whatever? horizontally
t  SELECTED PIPESt t PIPE       RECOMENDSt -------------------------t Look for-specialist       90%
 Steel-sodium-with.porous.media 40%
 Copper-sodium-with.porous.media 30%
tThe working temperatures depending on the fluid’s critical temperature to special applications or
when have no gravity help
```

Figure 3. Run 1. Case of high heat flux, safe working fluid, high operating temperature, high mass density, corrosive environment, and horizontal operating position

Figure 4 shows the second case, an opposite case from that presented in Figure 3, in which temperatures and powers are low, so the working fluids such as water, ammonia, and acetone appeared. In addition, the working position can be varied, requiring the presence of a porous medium.

```
CLIPS> (RESET)
CLIPS> (RUN)
Is the heat flux high > 20 W/cm2, medium until 20 W/cm2 or light until 10 W/cm2? low
Must the fluid be safe/toxic yes, no, unknown? unknown
Is the pipes Toperating range low (273K-400K), medium (400K-550K), high>550K, unknown? low
Is the weight importance low until 10000 kg/m3, medium until 6000 kg/m3, or high until 3000 kg/m3,
unknown? low
Is it works in corrosive environment yes, no, unknown? no
Does the pipe work horizontally, vertically or whatever? whatever
Is it a special application yes, no, unknown? no
t        SELECTED PIPESt t PIPE             RECOMENDSt ------------------t Look for-specialist
90%
 Aluminum-acetone-with.porous.media 40%
 Aluminum-ammonia-with.porous.media 40%
 Aluminum-water-with.porous.media 40%
```

Figure 4. Run 2. Operating temperature and low heat flux, working fluids such as water, ammonia, and acetone appear and horizontal working position

An intermediate case between the first (Figure 3) and the second (Figure 4) case is presented in Figure 5. In this situation, the number of possible heat pipe configurations increased due to many reasons. The non-corrosive environment allowed the application of all the available materials. Also, diverse working fluids can be recommended for an average temperature range, similar to those used for low temperatures. In addition, no porous media is required in the vertical position due to the gravity assistance in the fluid motion. Besides not being the best choice, the system also showed options of a heat pipe with porous structures that presented a lower percentage of recommendations.

```
CLIPS> (RESET)
CLIPS> (RUN)
Is the heat flux high > 20 W/cm2, medium until 20 W/cm2 or light until 10 W/cm2? medium
Must the fluid be safe/toxic yes, no, unknown? no
Is the pipes Toperating range low (273K-400K), medium (400K-550K), high>550K, unknown? medium
Is the weight importance low until 10000 kg/m3, medium until 6000 kg/m3, or high until 3000 kg/m3,
unknown? medium
Is it works in corrosive environment yes, no, unknown? no
Does the pipe work horizontally, vertically or whatever? vertical
t   SELECTED PIPESt t PIPE      RECOMENDSt ------------------------t Look for-specialist       91%
 Copper-methanol--without.porous.media 40%
 Copper-ammonia--without.porous.media 40%
 Copper-water--without.porous.media 40%
 Steel-methanol--without.porous.media 40%
 Steel-ammonia--without.porous.media 40%
 Steel-water--without.porous.media 40%
 Steel-methanol--with.porous.media 10%
 Steel-ammonia--with.porous.media 10%
 Steel-water--with.porous.media 10%
 Aluminum-methanol--with.porous.media 10%
 Copper-water--with.porous.media 10%
 Copper-ammonia--with.porous.media 10%
 Copper-methanol--with.porous.media 10%
 Aluminum-water--with.porous.media 10%
 Aluminum-ammonia--with.porous.media 10%
 Aluminum-water--without.porous.media 10%
 Aluminum-ammonia--without.porous.media 10%
 Aluminum-methanol--without.porous.media 10%
tThe working temperatures depending on the fluid’s critical temperature to special applications or
when have no gravity help
```

Figure 5. Run 3. The intermediate case

Appendix A and B show the validation table for the obtained combinations to check the results consistency between the ES and the specialist knowledge.

3.2. Development time of the specialist system

The developed specialist system consisted of the following activities:

- Knowledge acquisition: 15 days.
- Implementation of the knowledge base and development of the program's first version, which was tested to analyze syntax errors: 20 days.
- Second version (improvement of the prototype). It will be the presentation version.

4. Discussion

The obtained results validated the SE. When the system is fully chained, there will be 12960 possible combinations. At the current level of chaining, there are 96 possible outputs. The missing chaining level will be tested in the implementation of the new program functionality cycles. The validation of the system must consider the importance of the weight, toxicity, working position, and operating temperature. Results are compared with the information supplied by the specialist. If the importance of the weight is low, a less dense material can be used. On the other hand, if high, the density of the material cannot be large. The same conditions occur with the porous media. Even if you may not need porous media, the program will recommend cases with porous media; however, with a lower recommendation. The opposite condition is not possible. To clarify the scenarios, a function for the shell selection is shown in Figure 6.

```
(rule (if weight is low)
      (then best-shell is high))
  (rule (if weight is medium)
      (then best-shell is low with recommend 40 and
           best-shell is mean with recommend 90 and
           best-shell is high with recommend 10))
  (rule (if weight is high)
      (then best-shell is mean with recommend 30 and
           best-shell is low with recommend 90))
(rule (if weight is unknown)
      (then best-shell is low with recommend 10 and
           best-shell is mean with recommend 90 and
           best-shell is high with recommend 10))
```

Figure 6. Example of shell selection based on weight.

The recommendation results, shown in Figure 6, represent the diffuse percentual value, varying from 0 to 100. Taking this into account, the system validation became complex, being incomplete, i.e., it was not 100% performed. However, the comparison with the specialist information assessed the results.

5. Conclusions

An expert system based on fuzzy logic was developed, created on the knowledge of two expert volunteers. The life cycle for implementing the knowledge used the model of incremented functions, testing the quality of the results. The inference method consisted of direct chaining, in which the information is obtained by uploading questions in the program from the user. The main conclusions of the present work are:

- The developed expert system provided acceptable answers to the input data compared with the bibliography and the specialists (verification and validation). In addition, fuzzy logic was appropriate as decision support.
- The system can be expanded, providing successful cases of combinations of materials and working fluids to increase the functionality.
- The expert system proved to be a useful tool for the selection of heat pipe materials, which can be a routine activity for a specialist, but which needs expert knowledge to succeed in the device's design.
- The new expert system can be another tool for training researchers and designers in the heat pipe area.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Abbreviations and acronyms

CLIPS	C Language Integrated Product Software
ES	Expert System
FES	Fuzzy Expert System
q”	heat flux [W/m^2]
T	Temperature [K]

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Appendix A. Validation table for different combinations at low temperature applications.

Pipe combination name	Needs porous media	Validation 1	Validation 2	Validation 3	Weight importance	Validation 1	Validation 2	Validation 3	Toperating	Validation 1	Validation 2	Validation 3
(pipe (name Aluminum-water-with.porous.media)	(Porous-media yes)				(Shell high)				(Fluid medium low)			
(pipe (name Aluminum-ammonia-With.porous.media)	(porous-media yes)				(shell high)				(fluid medium low)			
(pipe (name Aluminum-acetone-With.porous.media)	(porous-media yes)				(shell high)				(fluid low)			
(pipe (name Aluminum-methanol-With.porous.media)	(porous-media yes)				(shell high)				(fluid medium low)			
(pipe (name Aluminum-sodium-With.porous.media)	(porous-media yes)				(shell high)				(fluid high)			
(pipe (name Aluminum-water-Without.porous.media)	(porous-media no)				(shell high)				(fluid medium low)			
(pipe (name Aluminum-ammonia--Without.porous.media)	(porous-media no)				(shell high)				(fluid medium low)			
(pipe (name Aluminum-acetone--Without.porous.media)	(porous-media no)				(shell high)				(fluid low)			
(pipe (name Aluminum-methanol--Without.porous.media)	(porous-media no)				(shell high)				(fluid medium low)			
(pipe (name Aluminum-sodio--Without.porous.media)	(porous-media no)				(shell high)				(fluid high)			
(pipe (name Copper-water-With.porous.media)	(porous-media yes)				(shell medium)				(fluid medium low)			
(pipe (name Copper-ammonia-With.porous.media)	(porous-media yes)				(shell medium)				(fluid medium low)			
(pipe (name Copper-acetone-With.porous.media)	(porous-media yes)				(shell medium)				(fluid low)			
(pipe (name Copper-methanol-With.porous.media)	(porous-media yes)				(shell medium)				(fluid medium low)			

Appendix B. Validation table for different combinations at high temperature applications

(pipe (name Copper-sodium-With.porous.media)	(porous-media yes)				(shell medium)				(fluid high)			
(pipe (name Copper-water--Without.porous.media)	(porous-media no)				(shell medium)				(fluid medium low)			
(pipe (name Copper-ammonia--Without.porous.media)	(porous-media no)				(shell medium)				(fluid medium low)			
(pipe (name Copper-acetone--Without.porous.media)	(porous-media no)				(shell medium)				(fluid low)			
(pipe (name Copper-methanol--Without.porous.media)	(porous-media no)				(shell medium)				(fluid medium low)			
(pipe (name Copper-sodium--Without.porous.media)	(porous-media no)				(shell medium)				(fluid high)			
(pipe (name Steel-water-With.porous.media)	(porous-media yes)				(shell low)				(fluid medium low)			
(pipe (name Steel-ammonia-With.porous.media)	(porous-media yes)				(shell low)				(fluid medium low)			
(pipe (name Steel-acetone-With.porous.media)	(porous-media yes)				(shell low)				(fluid low)			
(pipe (name Steel-methanol-With.porous.media)	(porous-media yes)				(shell low)				(fluid medium low)			
(pipe (name Steel-sodium-With.porous.media)	(porous-media yes)				(shell low)				(fluid high)			
(pipe (name Steel-water--Without.porous.media)	(porous-media no)				(shell low)				(fluid medium low)			
(pipe (name Steel-ammonia--Without.porous.media)	(porous-media no)				(shell low)				(fluid medium low)			
(pipe (name Steel-acetone--Without.porous.media)	(porous-media no)				(shell low)				(fluid low)			
(pipe (name Steel-methanol--Without.porous.media)	(porous-media no)				(shell low)				(fluid medium low)			
(pipe (name Steel-sodium--Without.porous.media)	(porous-media no)				(shell low)				(fluid high)			