



ETEKINA
Thermal energy recovery

D5.4 B. REPLICABILITY ANALYSIS MAKING TOOL

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Summary

This deliverable describes the main characteristics of the developed Replicability Tool that allows the user to do a first approach and quick evaluation of the use of Heat Pipe-Based Heat Exchangers (HPHE) technology for waste heat recovery in a defined scenario; composed by user defined hot source and cold sink streams characteristics. The user defines the scenario, introducing information about the kind of streams involved (air, water or exhaust fumes of natural gas combustion) their temperatures and flow rates. The tool recreates the recovery scenario by means of the analytical calculation of a range of HPHEs. The tool proposes HPHE solutions within a geometrical and construction parameters range under previously identified and bounded ranges. The results are approximate solutions based on boundary restrictions and assumptions. Afterwards, the tool allows the user to personalize the solution selecting parameters such as, the required thermal capacity of the heat exchanger; the minimum outlet temperature of the hot stream (to avoid the stream goes below the dew point and avoid condensation); the minimum outlet temperature of the cold stream (temperature that could be required by the thermal energy receptor process) and defining the selection criteria (minimum payback period, minimum volume or minimum weight) to be used for finding the personalized solution. In case of positive results, the user should consult the technology provider to confirm those preliminary results and go ahead with a more precise heat recovery systems design.

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Table of Contents

D5.4 B. REPLICABILITY ANALYSIS MAKING TOOL	1
SUMMARY	4
TABLE OF CONTENTS	5
INTRODUCTION	6
1. WAY OF WORKING	6
1.1. INITIAL DEPLOYMENT	7
1.2. ITERATION STEP E-NTU METHOD.	11
1.3. OPTIMISATION AND PERSONALISATION	12
2. ENERGY MODELLING	13
2.1. ITERATIVE ALGORITHM FOR E-NTU	13
3. ECONOMIC MODELLING	14
3.1. CAPITAL COST APPROACH	14
3.2. ECONOMIC INDICATORS	15
4. ASSUMPTIONS AND CONSIDERATIONS	16
4.1. FLUIDS, MATERIALS AND GEOMETRY CONSIDERATIONS	16
4.2. HEAT TRANSFERS EVOLUTION AND CONDITIONS	16
4.3. PRESSURE DROPS	17
4.4. SPECIFIC SOLUTION	17
REFERENCES	18



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Introduction

The replicability tool has been developed under task 5.4 to allow the HPHE technology manufacturer (and the RTDs involved in ETEKINA project that have acquired know how of HPHE prototypes performance in operational environment) to analyse in a simplified and quick way the technical and economic viability of HPHE solutions for waste heat recovery in a new scenario defined by a hot stream, as heat source, and a cold stream, as heat sink. In case the obtained results are positive and there are actual possibilities of the waste heat recovery system implementation, the HPHE technology provider will be contacted for the required detailed heat recovery systems design.

The tool has been built based on black box models so that the required input data are few and the results are quickly obtained in the order of some minutes.

The required input data are the mass flow rates, the temperature and the type of stream (air, water, combustion air, other) of the hot source and cold sink streams. Additionally, for selecting a possible solution, a recovery power value has to be selected from the resulted available range of the thermal capacity of the heat exchanger. Finally, information related to the energy prices and working hours is required for the economic analysis to obtain the payback period of the obtained solution.

1. Way of Working

The replicability tool works as follows:

1st step: Scenario Definition

- In the first step, the tool requires, from the user, the definition of the scenario, which includes the mass flows (kg/h), the temperature (°C) and the kind of stream (air, water, combustion air, other) of the hot source and cold sink streams

2nd step: Internal Simulation Process

- Then, the tool returns, after an internal simulation process, a range of HPHE solutions.

3rd step: Range of Solutions

- After that, the tool allows the user to visualise those solution maps that help to understand the limitations and capacities for the personalisation of the final solution. The solution maps include a wide range of geometric configuration for the heat exchanger, in order to provide a variety of solution. It includes number of pipes, configuration (row/holes), evaporator and condenser lengths.



4th step: Personalization

- By the personalisation of the solution, the tool searches among the solution maps in order to comply the criteria introduced by the user and returns the characteristics of the selected heat exchanger, within the exchanger recreated range.

1.1. Initial deployment

The tool runs in a MATLAB[®] environment: by means of the MATLAB[®] software or the MATLAB[®] Runtime. The MATLAB[®] Runtime is a standalone set of shared libraries that enables the execution of compiled MATLAB[®] applications or components.

The tool is developed in App Designer interface. App Designer is an environment that provides layout and code views, a fully integrated version of the MATLAB[®] editor, a large set of interactive components and a grid layout manager.

Once the tool is launched and the first main inputs are introduced (1st step: Scenario Definition), the tool calculates the heat capacity rate (mass flow rate multiplied by the specific heat of the fluid) of source and sink streams, the thermal energy available referred to the ambient temperature and the boundary conditions.

1.1.1. HPHE design and construction material

The following geometric and material parameters are pre-defined:

- The pipes are located with equilateral pre-defined staggered configuration
- The diameter and the thickness of the pipes are fixed.
- Bare tubes are considered (no finning)
- The heat exchanger housing material is steel.
- The materials of the heat pipes are SS304 and Carbon Steel. The thermophysical properties of construction materials have been considered constant.
- The considered internal is water or Dowtherm depending on the average temperature of the cold fluid and the hot fluid outside the pipe.
- The number of passes is limited not to be higher than double the number of rows.
- The pipes are aggregated in blocks/banks of a specific number of rows. The separation distance between blocks is fixed. The separation distance between the external pipes and the lateral walls is fixed.

The rest of geometrical or construction parameters, such as the number of pipes, the length of the pipes, the relation of the row and hole numbers, and the ratio of evaporator and condenser lengths, form part of the simulation variables.

1.1.2. Working ranges

The current version of the application limits the absolute mass flows and temperatures that user can introduce to the limits given hereunder. In case the user introduce a value outside



that limits a message is popped up saying that this values is not available and the application does not go ahead (i.e. “value must be between x and y”, where x is the lowest limit value and y is the highest limit value of the corresponding variable) . The limits imposed by current version of the tool are the following¹:

- From 150°C to 700°C for the hot stream temperature.
- From 15°C to 350°C for the cold stream temperature.
- From 100 kg/h to 22500 kg/h for the hot stream mass flow.
- And from 50 kg/h to 22500 kg/h for the cold stream mass flow.

Furthermore, some warning or error message have been implemented to notify the user if the case study is badly conditioned. The conditions are the followings:

- If the hot stream temperature is lower than the colder one an error message appears:
 - “Hot stream temperature must be greater than cold stream temperature.”
- If the hot stream temperature is only 20°C hotter than the colder one a warning message appears:
 - “Similar Hot stream & cold stream temperatures. The heat transfer may be harmed due to this low difference.”
- If the heat capacity rate² ratio is greater than 3 a warning message appears:
 - “Heat Capacity Rate > 3. The Heat Capacity of each stream differs considerably.”

1.1.3. Boundaries selection

In this first step, the ranges of the below mentioned geometric parameters are set based on some empirical approaches (developed by trial-error).

- number of pipes & pipe length,
- relation row-hole,
- relation evaporator length-condenser length.
- number of passes

These parameters calculated by the tool will establish the boundaries of the simulation ranges.

Number of pipes & pipe length

The ranges of number pipes and pipe lengths the tool will use are obtained by the empirical simulation of cases. These cases analyse the mass flow of the hot stream for some orders of

¹ These limits are a first approach of this tool version, in which the tool works in an acceptable way

² $(\text{Heat Capacity}_{\text{hot or cold stream}})^{\text{maximum}} / (\text{Heat Capacity}_{\text{hot or cold stream}})^{\text{minimum}}$

magnitude in which the mass flow of the cold stream and the temperatures of the hot and cold streams are changed. Other parameters in are maintained invariable (transverse pitch³ (St), longitudinal pitch (Sl), equilateral staggered configuration, bare tubes, pipe thickness and others).

The ranges of simulation have been established depending on the thermal properties of the fluid (in this first tool version only water and air have been considered). In this way, the final ranges of number of pipes and pipes lengths in which the tool is available to provide a reasonable solution (based on the ratio of heat capacity-rates⁴) are established for air-air streams scenario and for air-water, according to their flow rates and temperatures.

Ratio row-hole

The row is the number of pipes' rows counted in the direction of the flow (longitudinal); and the hole, is the number of pipes per row counted at the perpendicular of flow direction (transverse).

The ratio row-hole is defined as the relation between the number of rows of the heat exchanger and the number of holes per each row. This parameter defines the geometry of the HPHE device. A ratio near to 1 will suppose a squared plant/floor. Meanwhile, ratios that are far from unity, e.g., of 0.2 or to 5, will suppose a long and narrow or a short and broad plant/floor, respectively.

Besides, going beyond the construction issues, different configurations may affect directly to the heat transfers developed inside the system, a short ratio will increase the convection due to an increase in the turbulence fluid at the same time than the pressure drop is increased. This row-hole ratio parameter works together with the pipe length and the relative evaporator/condenser lengths relation for the final modus operandi of the HPHE device.

The range of the ratio row-hole parameter considered by the tool is the same for all the cases. This factor has not been bounded depending on the stream features, because all the solutions of that range may provide, in many cases, reasonable solutions under the energy point of view.

Ratio evaporator-condenser length

This ratio is defined as the evaporator length divided by the condenser length. In the heat pipe technology, one part of the heat pipe length is employed in the evaporator part (to make the internal fluid boil) and the other part, in the condenser (to make the internal fluid condense), as shown [Figure 1](#).

In this regard, some empirical relations in order to specify in a previous stage the simulation, based on the thermal properties of the fluid, are presented. This factor relates the area of convection of each part, and, therefore, it depends strongly on the heat capacity-rate of each stream to transfer heat.

³ The shorter distance from tube centre to tube centre between two adjacent tubes

⁴ $(\text{Heat Capacity}_{\text{hot or cold stream}})^{\text{maximum}} / (\text{Heat Capacity}_{\text{hot or cold stream}})^{\text{minimum}}$

The division between the condenser and evaporator factors situates the starting point for the final relation value. This ratio indicates the starting point from which the tool oscillates to propose a representative variety of hypothetical solutions.

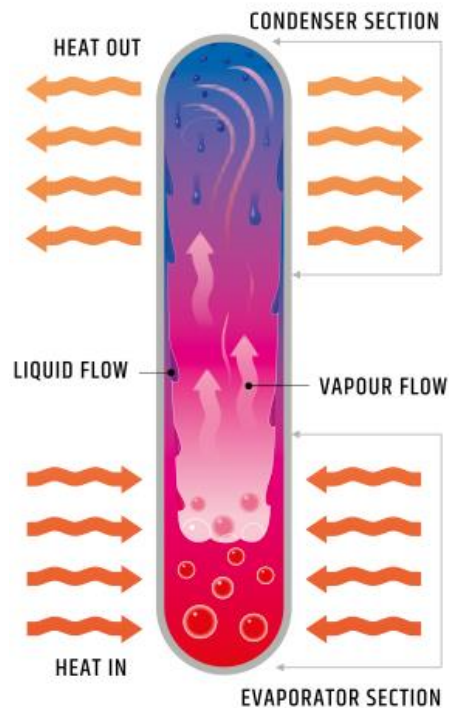


Figure 1. Principle of the heat pipe

The tool selects a proportional range up and down from this starting point based on the number of interval-simulations for this element (ratio evaporator-condenser). Then, the height of the evaporator is calculated for each simulation by the direct relation of this factor with the total height of the pipe.

Number of passes

In real HPHE cases, and in other heat recovery technologies such as shell-and-tubes, one stream may present more than one pass through the cross-sectional area in order to increase the forced convection phenomena.

In the tool, the obtained number of passes represents the times by which the fluid speed must be multiplied to achieve optimum heat convection values. This speed can be reached by increasing the number of passes or reducing the cross-sectional area. In order to develop more interesting solutions and to avoid solutions with slow fluid velocities (low heat convection phenomena), the tool selects for each specific case (within every range of iteration elements) the most suitable number of passes limiting the fluid speed.

1.2. Iteration step ε -NTU method.

Once the simulation bounds are defined for the specific scenario (cold and hot stream) the tool begins the iteration step. In this part, each available configuration which includes every combination among the previous defined elements ranges (number of pipes, pipe length, relation row-hole, and relation evaporator length-condenser length) is launched. Once a set of elements is defined the geometrical characteristics of the HPHE is obtained in each iteration. These characteristics include components such as front area for both parts (evaporator and condenser), the internal and external area of the pipes and other parameters such as the number of passes in case of HPHE with liquid fluid (water) as cold or hot stream.

The number of transfer unit (NTU) is a nondimensional parameter defined as following:

$$NTU = \frac{UA}{C_{min}}$$

where,

U is the overall transfer coefficient, $W/(^{\circ}C \cdot m^2)$,

A is the total transfer area, m^2 , and

C_{min} is the smaller heat capacity of the hot and cold fluids, W/m^2 .

The fluid heat capacity rate is defined by the multiplication of the mass flow rate multiplied by the specific heat:

$$C = \dot{m} \cdot c_p$$

where,

C is the fluid capacity rate (hot or cold fluid), W/m^2 ,

\dot{m} is the mass flow rate (hot or cold fluid), kg/s , and

c_p is the specific heat of the fluid at constant pressure, $J/(kg \cdot ^{\circ}C)$

Effectiveness (ε) is the proportion of the actual heat transfer versus the thermodynamically limited maximum possible heat transfer rate; which would be achieved if the temperature of the outlet of the cold flow would equal the inlet temperature of the hot flow [4]. It is defined by the following expression:

$$\varepsilon = \frac{q_{act}}{q_{max}} = \frac{C_c(T_{h,i} - T_{h,o})}{C_{min}(T_{h,i} - T_{c,i})} \text{ and } \varepsilon = \frac{C_c(T_{c,o} - T_{c,i})}{C_{min}(T_{h,i} - T_{c,i})}$$

where C_h and C_c represent the heat capacity of the hot and cold flows, respectively.

Effectiveness is a dimensionless parameter with a value between 0 and 1; theoretically only a heat exchanger of infinite area would be able to achieve an effectiveness of 1.

The NTU represents the size of the heat exchanger. For each capacity ratio there is an asymptotic relation between the effectiveness and the NTUs. The higher the NTUs, the higher is the effectiveness of the heat exchanger reaching asymptotically its maximum; for small NTUs, the heat exchanger effectiveness is low.[4]

The ε -NTU analysis of a HPHE is done by separating it into the two separate heat exchangers for each section of the heat pipe (the condenser and the evaporator) being coupled by the working fluid. The effectiveness of the evaporator and the condenser section of the heat exchanger are determined separately and are given by [5] :

$$\varepsilon_e = 1 - e^{(-NTU_e)} \text{ and } \varepsilon_c = 1 - e^{(-NTU_c)}$$

The number of transfer units for the evaporator and for the condenser are calculated separately as two heat exchangers [5] :

$$NTU_e = \frac{U_e A_e}{C_e} \text{ and } NTU_c = \frac{U_c A_c}{C_c}$$

where,

A is the total heat transfer area in the respective sections of the evaporator or condenser, respectively, A_e and A_c ,

C, is the average heat capacity rate of the respective shell-side fluid of evaporator and condenser sections C_e and C_c , respectively.

U is the overall heat transfer coefficient calculated for the evaporator and condenser sections respectively (U_e and U_c).

Based on the ε -NTU algorithm method for calculation of the energy characteristics of HPHEs, the iteration step supposes an initial U_e and U_c and the effectiveness of the system is calculated in order to go into the convergence algorithm (first other initial variables and parameters are initialised). This convergence algorithm consists of an iterative cycle (“while” in Matlab code) which compares the “cold side temperature” obtained from the analytical simulation process with the established “cold side temperature” (introduced by the user).

Once the tool has created an analytical HPHE, the calculated U_e and U_c are obtained, and the iteration starts again until the temperatures obtained for the simulation and the temperature introduced by the user converged to the same value within a tolerance value. The way in which the tool works to obtain this final temperature is explained (Nusselt, Reynolds, pressure drop and other equations...) in Energy Modelling chapter 2

Due to the design of the model, cases that take too much computational time to arrive to the solution may appear. If the loop exceeds a specific number of iterations and the convergence is not achieved, this case and its results are not considered as solution.

1.3. Optimisation and personalisation

In the last step, the user can define parameters or conditions to select/personalize one solution among the ones found by the tool. The user can select parameters such as, the required thermal capacity of the heat exchanger; the minimum outlet temperature of the hot stream (to avoid the stream goes below the dew point and avoid condensation); the minimum outlet temperature of the cold stream (temperature that could be required by the thermal



energy receptor process) and can define the selection criteria that tool will use for finding a solution with the minimum payback period, volume or weight.

2. Energy Modelling

The tool used analytical correlations obtained from literature (Figure 2) to calculate the heat transfer and pressure drop.

Info	Heat transfer	Pressure Drop
Bare tube bank (Stagg.)	Zhukauskas (NL>10)/Grimison	<i>Heat Exchanger Design Handbook (1983)</i>

Figure 2 Used Heat transfer and pressure drop correlations.

The heat transfer correlations have been obtained from Zhukauskas [1], in case of the number of lines of tubes (number of rows in ETEKINA project nomenclature) is higher than 10, and from Grimison [2], from 1 to 9 lines of tubes.

The pressure drop correlations have been obtained from Heat Exchanger Design Handbook (1983) [3].

To be possible the heat transfer between the involved two streams, both streams have to be moved through the exchanger. The movement of the streams is produced by the fans or pumps that require an energy consumption to make possible the fluids movement. The energy required depends on the pressure drop caused by movement of the fluid through the heat exchanger.

The heat transfer and the pressure drop of a heat exchanger are the main aspects that define its performance. The pressure drop is caused by the friction and by the turbulence of the fluid in the heat exchanger. As higher is the turbulence higher is the heat transfer but at higher energy requirement to move the fluid. It is important to keep the pressure drop within the design values not to produce excessive friction and consumption in the use of heat exchangers.

2.1. Iterative algorithm for ϵ -NTU

The model supposes the temperature of the cold stream at the output until the temperature of the cold stream at the input converge (within a tolerance) with the value introduced by the user (within a tolerance). The system changes/updates the NTU value of the previous iteration by including a variation generated by an auto-adaptative algorithm.

The employed algorithm works as follows:

- **First, the model sets a first approach pair of constants for the overall heat transfer coefficients of the condenser and the evaporator to initialize the system.**
- **The system effectiveness is defined.** Based on the previous initialization values and on the geometrical characteristics of the specific case, the final effectiveness of the system is defined.
- **Iteration procedure: Thermal convergence criterion.** Here, the script leads to a final unique solution. Based on the effectiveness of the system the code generates a virtual HPHE case by means of the calculation of the output temperatures (evaporator and condenser), which will be introduced in the heat transfer equations. With this preliminary approach, the code obtains the “final” output temperatures and the “final” overall heat transfer coefficients (condenser and evaporator). The procedure is repeated until the final output temperature of the condenser leads to the value provided by the user.
- **Solution – Pressure drop calculation.** Once the system has converged, the pressure drops of the evaporator and condenser are obtained.

3. Economic Modelling

The economic modelling of the tool takes into account the costs and saving and provide an economic evaluation based on some energy-economic indicators. The costs are represented by means of the capital cost (CapEx) approach of the heat exchanger unit, the assumption of the operational cost (OpEx) of the system (both Operation & Maintenance tasks of the unit and the new equipment operational cost). The savings branch covers the savings related to the energy bill (fuel and electricity) and the carbon emissions reduction (estimated based on European Emission Trading systems [8]). Finally, some indicators related to the investment and the energy consumption are obtained.

3.1. Capital Cost Approach

As it has already described, based on the input data (hot and cold source) the tool generates diverse heat exchanger solutions for HPHEs. The capital costs of those recreated heat exchangers are calculated in that initial step to be used at the ulterior economic analysis of the tool.

The construction cost derived from other features of the system, such as anti-corrosion lining, pressured zones or other special characteristics are not taken into account due its complexity and impossibility to model or analyse this scenario with the tool.

Due to the novelty of the technology of the heat pipes on the generation of heat exchanger there is not a cost graph, nor power law capacity cost function as exist in other engineering



systems (pumps, cooling tower, electric motor, etc.). The cost assumption for the HPHE is based on the expertise/work of the developers of the technology and the construction costs. The construction costs are obtained based on the geometrical characteristics of the heat pipes which provide the final mass of materials required for this unit. The transportation costs are also included in the approach, both for the material and for the final unit transportation to site.

Variables	Unit
Cost of carbon steel	€/kg
Cost of SS304	€/kg
Cost of manufacturing each heat pipe	€/piece
Cost of distilled water	€/kg
Cost of dowtherm	€/kg
Labour rate	€/ Labour-day
Electricity consumption factor with respect to HPHE capacity	number
Electrical energy price	€/kwh
Cost of paint	€/litre
Transportation cost rate for material supply to HPHE plant	€/tkm
Average transport distance for HPHE material supply	km
Transportation cost rate to deliver HPHE to site	€/tkm
Average transport distance of HPHE to site	km

Table 1 Main cost parameter for HPHE final cost.

In this regard, the final cost is obtained as the sum of the diverse materials and manufacturing labours.

$$C_{HP} = [C_{SS304} + C_{CS} + C_{pipeFluid} + C_{TransDeli} + C_{TransSupp} + C_{ManuPipes} + C_{Paint} + C_{ManuElect} + C_{ManuLabour}] * f$$

In which C_{Paint} , C_{SS304} , C_{CS} and $C_{pipeFluid}$ correspond to the costs of the paint, stainless steel, carbon steel and pipe internal fluid; $C_{TransDeli}$ and $C_{TransSupp}$ correspond to the transportation costs and $C_{ManuPipes}$, $C_{ManuElect}$ and $C_{ManuLabour}$ correspond to the manufacturing labours of the pipes, the electrical cost of this works and the assembly labours costs. f represents the overcost factor with respect to variable cost and the profit factor of the manufacturers.

3.2. Economic indicators

As a conclusion of this assessment, three economic indicators are approached: Levelized Energy Efficiency Cost (LEEC), Simple Payback Period (SPP) and the Return of Investment (ROI) for each heat exchanger. The LEEC indicator proposed by Chiaroni et al. [11], correlates the energy savings that can be achieved through the implementation of an energy efficiency technology and the total costs incurred throughout the entire life cycle of the technology, e.g., initial investments, O&M, disposal costs. Therefore, this indicator returns the real cost

of the energy provided by this implementation. However, this indicator is modified to be adapted to the desired number of years of the analysis (disregarding the disposal costs). The single payback period, SPP, accounts for the time required to recover the cost of an investment, with zero interest rate, while the Return of Investment, ROI, measures the gain or loss generated by an investment in relation to the amount of money invested (for a specific period).

$$SPP \rightarrow \sum_{t=0}^{SPP} CF_t \geq 0$$

$$LEEC_T = \frac{\sum_{t=0}^T (CapEx_t + OpEx_t)}{\sum_{t=0}^T TES_t}$$

$$ROI_T = \frac{CF_t}{(CapEx_t + OpEx_t)} \cdot 100$$

where CF [€] considers net cash inflows during the period “t” [years]. The term TES represents the Total Energy Savings generated by the heat exchanger.

4. Assumptions and Considerations

4.1. Fluids, materials and geometry considerations

The current version of the tool works for air, water and exhaust fumes of natural gas combustion fluids and for a limited temperature and flow rate ranges.

The heat exchanger materials and some geometric parameters are pre-defined and fixed

The boundary range conditions within the tools recreates the possible heat exchanger solutions are previously bounded.

4.2. Heat transfers evolution and conditions

There is not any consideration or degrading conditions taken into account in order to simulate the dust particles and the sticking phenomenon to the heat pipes walls.

The tool provides a stationary way of working for an already developed flow and surrounding conditions.

Other heat losses related to losses through the surface of the collectors or to the inlet or outlet sections, or to the piping from the exhaust system (source) to the device and from the device to the system in which the heat is employed (sink) are not assumed.

The heat losses through the surface of the device are introduced in the code but not activated. It is designed to calculate the heat losses in each differential of length (in the sense of the flow) both for the evaporator and condenser.

4.3. Pressure drops

The pressure drops calculated by means of the tool only taken into account the losses due to the effect of the pipes inside the HPHE system. Other losses related to the collectors or to the inlet or outlet sections (loss coefficients for transitions), or to the piping from the exhaust system (source) to the device and from the device to the system in which the heat is employed (sink) are not assumed.

The losses produced due to other flow instabilities or due to the changes in the direction or sense of the flow, expansions or contractions, collector entrance, are not accounted.

4.4. Specific solution

The range of solutions reproduced is product of a combination of several ranges of independent construction parameters. These ranges contain a certain number of divisions which, ultimately, make the specific configuration of each solution.

As it is not defined a differential interval (infinitesimal fractions) within these ranges, the analytical optimum solution for some specific criteria may be hidden into this partition. The ranges and intervals are selected due to a previous empirically analysis for the possible cases.



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