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# PROJECT OF A NUCLEATE POOL BOILING TEST RIG FOR HIGH PRESSURE AND HIGH TEMPERATURE

**Arthur Vieira de Oliveira**
**Rogério Gonçalves dos Santos**
UNICAMP – Rua Mendeleyev, 200, Barão Geraldo, Campinas, SP, Brazil
arthurvo@yahoo.com.br
roger7@fem.unicamp.br

***Abstract.*** *With the expansion of boiling research, several test concepts and methods were created to study this phenomenon. Controlling all the parameters to assure correct results is one of the challenges when projecting boiling rigs. Lots of phenomena must be considered during the design: thermal expansion, thermal insulation, structural strength, leakage, data acquisition, imaging, and others. The challenge is even greater when working with extreme conditions, specially the safety aspect. Thus, numerical simulation takes an important role during the project phase. This work presents a design of a pool boiling experimental rig that works at high pressure and high temperature. Papers about this topic were studied and their test rigs were investigated in each part, gathering enough data to project a well cost-effective one. The model with a transparent cylindrical chamber was chosen to be designed, as it favors the phenomenon visualization. It is important to be sure that all the measures will be exact and precise and the rig will withstand all the mechanical and thermal loads. Therefore, structural and thermal numerical simulations were performed to evaluate the dimensions, to choose the right materials for each part and to guarantee the reliability of the data acquisition. With the structural analysis, the glass tube and the steel supports were dimensioned. The sealing was as well studied to avoid leakage, since it is more probable to happen with high pressures. Thermal simulation was used to estimate the chamber heat loss. Also, the effectiveness of the thermocouple measurements on the test section was assessed and the calculation of the heat flux during boiling was numerically validated. After assuring all the parameters are under control and all the parts are properly designed, the test rig is ready to be built.*

***Keywords:*** *Pool boiling, Nucleate Boiling, Test rig, Project, Simulation*

## 1. INTRODUCTION

After boiling was first described by Shiro Nukiyama in the 1930s, it has taken the academic attention. It is because this phase changing process is one of the best methods to transfer heat. In other words, this is a relatively fast way to heat a cold fluid by a hot surface or to cool a hot surface with a cold fluid. For this reason, this phenomenon has been being widely investigated and studied all over the world. A very large data has been gathered since the beginning. Studies with hundreds of pure fluids; binary, ternary and multi-components mixtures; pool and flow boiling; and several kinds of surfaces and conditions can be found in the literature and journals.

Nowadays, the trend in boiling research is to understand completely this chaotic phenomenon and to study complex situations (for example, boiling in microtubes or numerical methods for flow boiling). In the case of pool boiling, it is always generating new boiling curves of different fluids. The bubble generation and its behavior are also studied with pool boiling test rigs, as well as experiments to validate numerical calculations. All these studies can be performed involving large temperature and pressures ranges, which mean it needs robust test rigs.

There are lots of test rig concepts that are able to study lots of situations. Usually, the more complex and particular the study case, the more expensive the experimental rig is. In flow boiling research, it may cost some hundreds of thousands of dollars. Nevertheless, some simple solutions can be used to try to decrease the bench cost.

In this study, we gathered several solutions for each part of a pool boiling test rig. Some examples are firstly discussed to introduce some existing solutions. All the information was summarized in a mind map, where it is easier to analyze and choose the more appropriate solutions. Each suggestion is discussed to understand its best application. Finally, the most cost-effective ones were chosen to integrate our concept.

After all the elements were defined, we performed numerical simulations to guarantee that every component would work as expected. In other words, the calculations verified that the structure would withstand well the mechanical and thermal loads and the acquired data would be reliable to be processed and studied. As said, since it is a quite costly project, it is very important to assure the test rig is well projected. In this case, the test rig was designed to resist a 10 bar pressure and a work fluid at 150ºC. Moreover, we preferred to use transparent materials to enable the phenomenon visualization.

## 2. THE PROJECT OF A NUCLEATE POOL BOILING TEST RIG

Firstly, articles, dissertations and thesis were read to collect enough data about the existing concepts of pool boiling test rigs all over the world. Many solutions to study the most variable conditions could be found. Usually a pool boiling

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test rig is specific to study nucleate, transition or film boiling. Also, it is designed for a particular purpose. If it is designed to study the bubble generation or its behaviour, it is not very good to acquire a boiling curve; if the boiling curve is the desired result, the visualisation may not be very clear. If it is projected for boiling on a flat surface, it is not usually applicable to cylinders, and the other way around. If it works at saturation temperature it is not very useful for sub-cooling studies. And it goes farther.

In the present work, the project is directed to study nucleate boiling of ethanol at saturation temperature only, therefore all the discussion will be focused in this application. This kind of test rig is basically composed by six parts: the boiling chamber, the pre-heating system, the condenser, the test section, the data acquisition system and the image acquisition system. The boiling chamber is where the work fluid is and the boiling will take place to be studied. The pre-heating system heats the work fluid until the saturation temperature and maintains it during the test. The condenser is necessary to avoid pressure increase in the boiling chamber. The test section is the part that will be heated and will act as the boiling hot surface. The data acquisition system is necessary the gather all the information collected by the thermocouples, pressure transducer, and others. The image acquisition system is usually a high-speed camera that films all the experiment to after analyse the results together with the images of the phenomenon. Each of these parts can be subdivided in more components, but it is not necessary for the present study.

Several solutions for each system were studied, except for the data and image acquisition systems. This is because the existing solutions are basically the same. For the image acquisition, it is necessary a high-quality high-speed camera, because the phenomenon takes place fast enough so a common camera cannot catch it properly. For the data acquisition, there are more ways out. Thermocouples or thermography are solution to evaluate the surface temperature and the heat flux, however to measure the bulk temperature it commonly uses thermocouples.

Some of the test rigs studied will be presented in the following sections. Their characteristics, advantages and disadvantages will be analyzed. It does not mean the ones that are not included in this discussion are less important or less contributive. However, all the references are listed in the end of this paper.

### 2.1 UFSC Test Rig

In Cardoso and Passos (2011), the test rig is designed to perform tests with refrigerants. Therefore, the temperatures involved in the processes are not high. The boiling chamber is a cylindrical acrylic tube, while an external flowing fluid (water) controls the work fluid temperature. The degasification is done outside the test rig and, afterwards, the fluid is taken to the before vacuumed boiling chamber. The test section is a thin copper sheet with three thermocouples placed in its bottom. As the temperatures are not high, the test section is insulated with a PVC body. The condenser is placed inside the boiling chamber.

Two isothermal bathes with flowing fluid, being one cold and the other one hot, are used in this concept. The hot one is used to pre-heat the work fluid and keep it at a desired temperature. The cold one circulates through the condenser.

This test rig concept is more complex than most of the ones in pool boiling research. In the other hand, it allows the performer to easily control all the boiling parameters. It is interesting to notice the possibility to confine the hot surface in this test rig. It significantly increases the research capability of this group.

### 2.2 POSTECH Test Rig

In Jo and Kim (2011), the boiling chamber is an octagonal aluminium body. It works at higher temperatures and pressures than common test rigs. The pre-heating is done by an immersed resistance controlled by a Proportional-Integral-Derivative (PID) controller connected to a type K thermocouple. The test section used to perform the test was a thin silicon wafer with a thin-film heater attached to its bottom face. They considered the surface temperature as the heater resistance temperature, which was calculated with the tension and the current passing through it. As well, the heat flux was defined as the energy lost by Joule effect (the product of the current with the tension). The image acquisition system is done with a high-speed camera, which is positioned in front of a window made in the aluminium body for visualization. The degasification is done within the boiling chamber by heating the work fluid for 2 to 3 hours. One interesting solution in this concept is that the condenser is placed “outside” the boiling chamber. Hence, the test chamber has a reduced volume, consuming less material in its construction.

Although this is a simpler and effective test rig, the bulk temperature control is more difficult if you don’t have an appropriate thermal insulation. Furthermore, this method to measure the surface temperature and the heat flux should be validated somehow (for example, with numerical simulation).

Even though there are windows for the phenomenon visualization, this model of test bench is not the most recommended for tests that require very good imaging. However it complies very well with this experimental rig purpose.

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### 2.3 MIT Test Rig

This test rig was used by Forrest and Cohen (2010). The boiling chamber is submersed in an isothermal bath, which has its temperature controlled by an immerse resistance. The degasification is also done within the boiling chamber by heating the fluid for a couple hours. The test section is a nickel wire and the evaluation of its temperature and the heat flux through it is done by measuring the voltage and the current. This method has very good results when the test section is a wire. The condensation system is not discussed.

This solution is excellent to control boiling parameters. Nevertheless, the paper does not discuss enough about the test apparatus to evaluate its limitations.

### 2.4 Indian Institute of Technology Madras Test Rig

Rao and Balakrishnan (2004) use relatively small quantities of work fluid in their boiling experiment. They don't specify how the fluid degasification neither the pre-heating are performed. The boiling chamber thermal insulation is done using a vacuumed doubled-wall glass. The test section is a funnel shaped aluminum block, where four thermocouples are placed vertically in its smaller diameter. That way, it is possible to calculate the surface temperature and the heat flux using one-dimensional Fourier Law. The condenser is placed inside the boiling chamber.

As the boiling chamber wall is made of glass, the phenomenon visualization is clear from every angle. However, if the glass is not thick enough, the test rig may not support high pressures.

### 2.5 Mind Mapping Concepts of Nucleate Pool Boiling Test Rigs

Since the objective of this project is to study nucleate pool boiling of ethanol at high pressure (10 bar) and, hence, high temperature (the saturation temperature at this pressure is 150ºC), the test rig must be very robust. Furthermore, it is interesting to make possible the study of the most kind of fluids and conditions. Thus, it is also desired the test rig to be inert and as large as possible.

After all the research about nucleate pool boiling test apparatus, it could be seen that there are a lot of information dispersed in the literature. It became necessary assimilate all the ideas and concepts available in papers and books. To ease this study, some solutions found for each part was summarized in a mind map (Fig. 1). FreeMind was the software used to create it.

The mind map is firstly divided by the major parts of a nucleate pool boiling test rig. Only the image acquisition was neglected in this study because using a camera (preferably a fast one) is the only solution. From this diagram, it is clearer to analyze the solutions and ideas for each component. Depending on the type of study intended to do, one specific solution will be more appropriate than another one. If two or more solutions may fit in the requirement, it can be chosen the cheapest or the one that allows better controlling.

For the condensation device, it basically needs to be determined if it stays within or without the boiling chamber. The main difference is if it is inside the chamber, it fills more space than the other one. Moreover, if the work fluid is at high pressure, it may be structurally more significant, because the load will be applied on a larger surface. One thing to pay attention when placing the condenser is to not allow the condensed droplets to disturb the boiling test.

The only solution found for the pre-heating inside the boiling chamber was the immersed heater, which is also the cheapest solution. If this proposal is chosen, it must be careful so it does not enhance the fluid motion by convection, which can affect significantly the test results. All the other solutions available take place outside the boiling chamber, like the solutions of the UFSC and the MIT test rigs. A third existing idea is heating the work fluid at a separated chamber. The only difficulty in this case is to put it in the main chamber without disturbing the boiling. It is more commonly used in studies about subcooled boiling, where the pressure is not controlled by the fluid temperature. This method was used by Park et al (2009).

The temperature acquisition, as said, can be performed using thermocouples, the most common solution, or thermography. To measure the bulk pressure, both pressure transducers and pressure gauges can be used. The advantages of transducers are it provides more accurate measures and it can be used as input to controllers. Nevertheless, pressure gauges are very cheap solutions (costs 6 to 10 times less than pressure transducers).

The test section definition is strongly dependent of the study objective, in special its shape and the heating method. Studies have confirmed that heating the test section by Joule Effect and by a passing hot fluid may have different results. However, two topics are quite general about this component: the thermal insulation and its fixing. If the heat flux calculating method is the product of the tension and the current, it must be guaranteed that all the electrical power converted in thermal energy is directed to boiling. That is the need of a good thermal insulation. Moreover, if the insulator is not tight or aligned well with the test section, bubbles can be nucleated in this contact. It can affect considerably the test results, because these bubbles will enhance the convection around the hot surface, producing incorrect results.

Finally, there are four main decisions to take about the boiling chamber: the phenomenon visualization, the chamber thermal insulation, the fluid degasification and its material. The observation of the boiling process is extremely

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important to understand and to check how the experiment is carrying on, besides matching the boiling behaviour with the data acquired or calculated. The chamber thermal insulation is essential to avoid heat loss of the work fluid. It helps to keep it at the saturation temperature. The fluid degasification is necessary to loose dissolved non-condensable gas in the fluid. If these gases apart during the test, it will too enhance the convection, disturbing the results. The test rig material is basically decided depending on its purpose. If it is desired to enrich the visualization, transparent materials are preferred. If it will work at high pressures, strong material, such as steel, could be chosen.

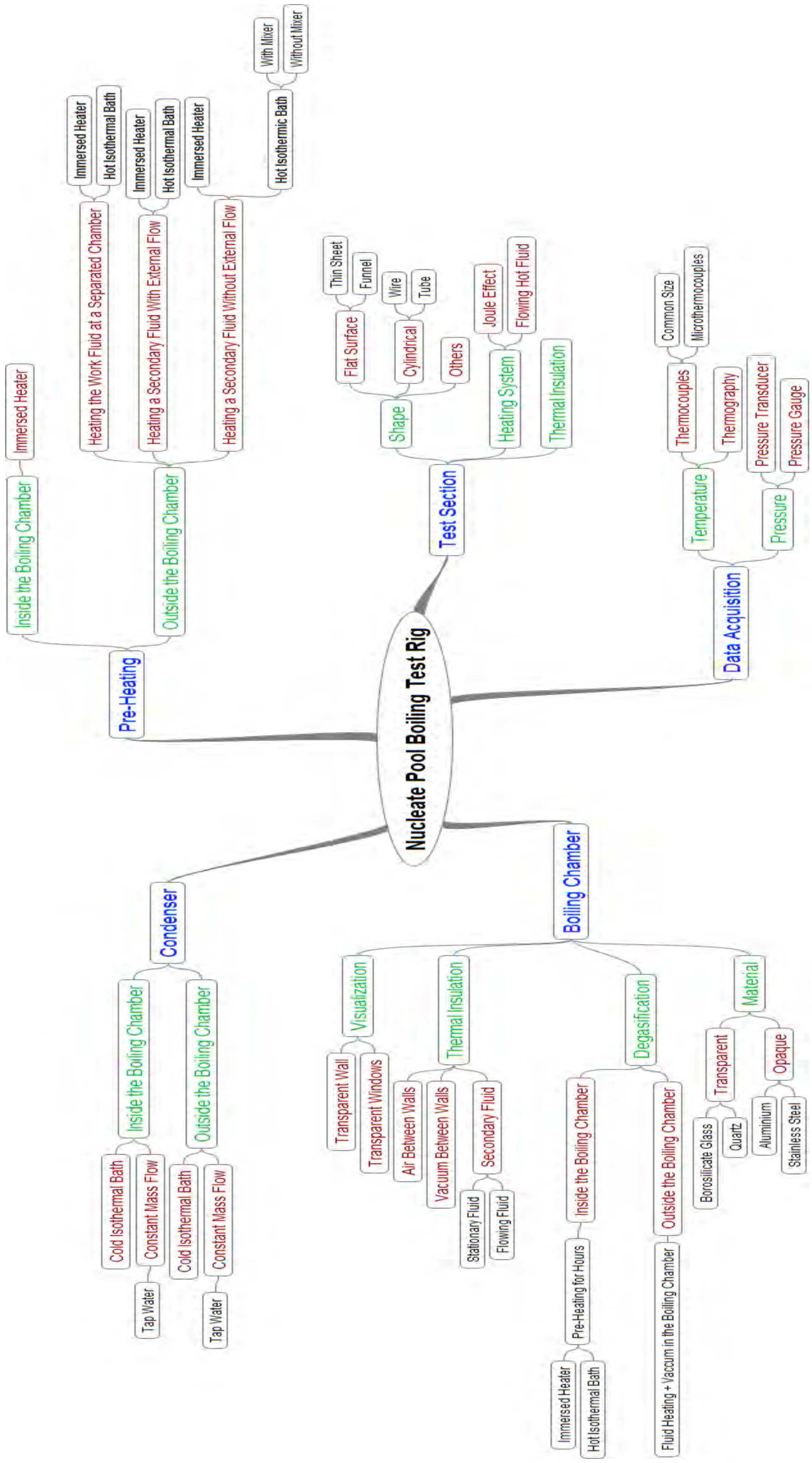


Figure 1. Mind map with several solution for each component of a nucleate pool boiling test rig

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## 2.6 The Purposed Test Rig Concept

The parts chosen to compose our test rig concept are the following:

1) The boiling chamber will be as transparent as possible, in order to allow at best the phenomenon visualization. Hence, the wall will be made of borosilicate glass tube and the top and the bottom will be two 316L stainless steel slabs. Both materials are inert to a large quantity of fluids. Caution is needed when measuring the bubbles dimensions, because this shape acts as lens, projecting images larger than the object actual size. This proposal is very similar to the UFSC test rig in Cardoso and Passos (2011).
2) The pre-heating system will be performed by an immersed heater. It will as well be made of stainless steel. This is the simplest and cheapest method to heat the work fluid. It must be placed in the upper zone, so the convection that it induces will not interfere in the boiling. Any induced fluid motion that is not caused by boiling may affect the test results. The heater power will be controlled by a PID controlled, which its input will be a thermocouple that will immerse in the work fluid. Jo and Kim (2011) used this same solution in their test rig.
3) The condenser will be outside the boiling chamber. This way, the volume occupied by vapour is decreased. The place where the condenser will be placed will be removable, so the cleaning can be done through its hole and it is not necessary to unset the whole test rig. This was also used by Jo and Kim (2011).
4) The test section will also be removable. Therefore, it can be replaced by test sections of many kinds and shapes. It only needs to be fixed in a Teflon® case, so it can be set in the test rig. For boiling on flat surfaces, it will be used a copper funnel structure with thermocouples placed vertically (same solution of Rao and Balakrishnan (2004)).
5) All the temperature acquisition will be made by thermocouples, while the pressure will be measure with a pressure gauge. One thermocouple must be placed in the vapour region to measure its temperature.
6) The thermal insulation will be an air column between the borosilicate glass and a clear polycarbonate tube, which will also work as a protection if the glass fails. To decrease the heat loss through the metallic slabs, it will be covered with stone wool.

Figure 2 presents a 3D model of the nucleate pool boiling test rig under construction. In the figure it is without the stone wool in order to better visualize the components of the experimental rig. The numbers in the figure presents each component and where it is placed.

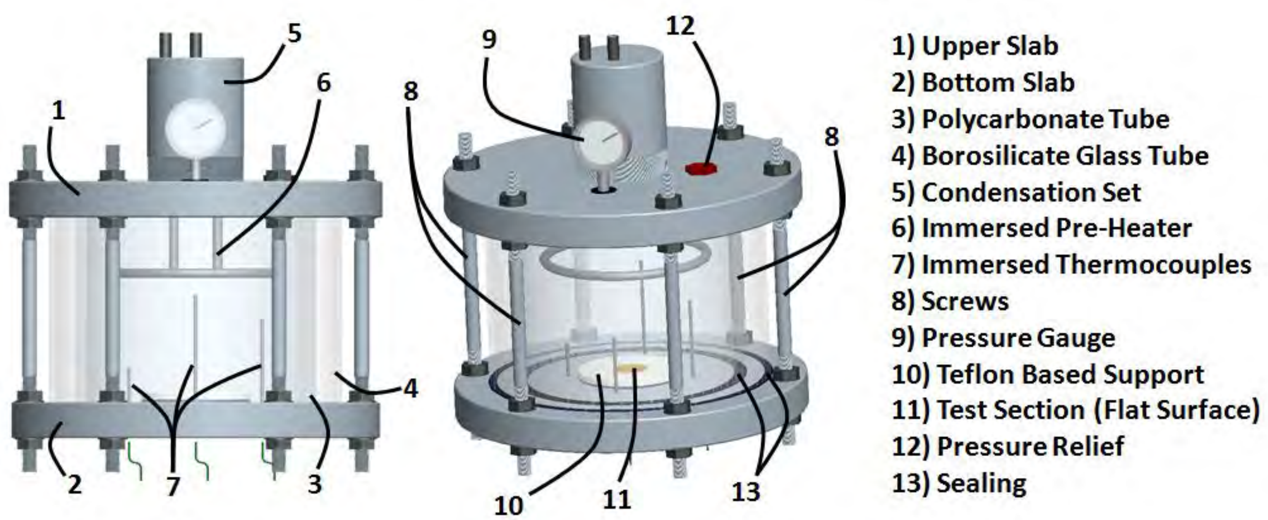


Figure 2. Nucleate pool boiling test rig developed for high pressures and high temperatures

After the concept was created, the parts must be dimensioned, the boiling chamber heat loss must be evaluated and the temperature acquisition in the test section must be validated. All these steps were performed with numerical simulation using the software ANSYS 14.0 Workbench.

## 3. THE NUMERICAL VALIDATION

Numerical simulation is a safe way to pre-guarantee that all the parts in the nucleate pool boiling test rig will comply with their purpose. From this calculation it is expected to assure that:

1) The experimental rig will withstand the mechanical and the thermal load.
2) The boiling chamber sealing will withstand the inside pressure.
3) The boiling chamber will not lose the least heat possible, so the immersed heater can keep the bulk temperature constant.
4) The thermocouples in the test section will measure correct temperatures. In other words, assure that it is measuring the temperature of the test section at the point where it is placed.
5) The 1-D Fourier Law equation is valid to calculate the surface temperature and the heat flux using the data acquired by the thermocouples in the test section.

Table 1 lists the materials used for the simulation and their properties.

Table 1. List of material properties used in the numerical calculation

| Material | Density [kg/m³] | Young's Modulus [GPa] | Poisson's Ratio | Coeficient of Thermal Expansion [$^oC^{-1}$] | Thermal Conductivity [W/(m.K)] | Failure Criteria |
|---|---|---|---|---|---|---|
| ***Structural Steel*** | 7850 | 200 | 0.3 | -- | 60.5 | *Yield Stress* 350MPa |
| ***Stainless Steel*** | 7750 | 193 | 0.31 | -- | 15.1 | *Yield Stress* 290MPa |
| ***Borosilicate Glass*** | 2230 | 64 | 0.2 | $3.0.10^{-6}$ | 1.14 | *Ultimate Stress* 10MPa *Max. Temperature* 200ºC *Max. Temp. Difference* 120ºC |
| ***Polycarbonate*** | -- | -- | -- | -- | 0.17 | *Max. Temperature* 130ºC |
| ***Sealing*** | 1810 | 0.1 | 0.45 | -- | 0.15 | *Max Temperature* 200ºC |
| ***Stone Wool*** | -- | -- | -- | -- | 0.045 | -- |
| ***Air*** | -- | -- | -- | -- | 0.0242 | -- |
| ***Copper Alloy*** | -- | -- | -- | -- | 401 | -- |
| ***Teflon®*** | -- | -- | -- | -- | 0,35 | *Max Temperature 260ºC* |

Since the present work is not focused in simulation methodology, it will not be presented the mesh validation. However, in every simulation it is guaranteed that the mesh was refined enough. The main objective of this paper is to present a concept of nucleate pool boiling test rig that supports high pressure and high temperatures. The simulation was performed only to verify that this concept theoretically works and to dimension and assess the critical components of the test rig.

### 3.1 The Sealing

The flat sealing will be made of Viton® and its thickness is 3.2 mm. This material choice is mainly based on its high chemical resistance to fuels and its good stability at temperature up to 200ºC. As the maximum temperature found in the test rig is 150ºC, thermal resistance will not be a problem.

To calculate the necessary compression to avoid leakage, it will be taken its compressive characteristics. However, for the simulation performed in ANSYS, in order to simplify the calculation, it will be modelled as a very elastic material, like rubber. Consequently, only the results acquired for the sealing in the mechanical simulation will not be realistic. Nevertheless, it will not affect the results for the other components. As the sealing thermal conductivity in Tab. 1 complies with Viton®, the thermal simulation will be realistic for every component.

Based on the website of Mosites Rubber Company (2013), the *Viton® A compound #10138* may be useful in this project. With 15% compression deflection, its compressive strength is around 1.65 MPa, which is higher than the boiling chamber internal pressure. Therefore, that will be the displacement applied on the Viton® to avoid leakage in the test rig.

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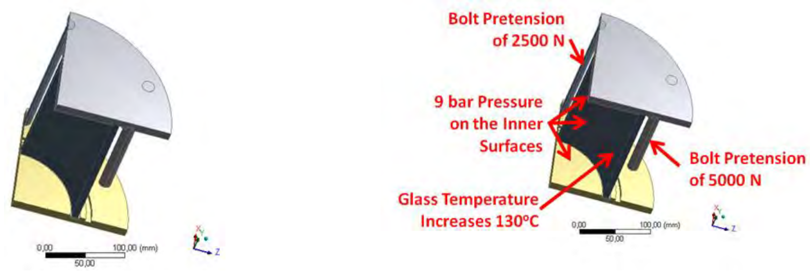
### 3.2 Mechanical Loads Simulation

The mechanical loads the test rig will be submitted to are: the bolts pretension (to keep the boiling chamber sealed), the inside pressure (when the fluid achieve the saturation temperature) and thermal expansion, which will only be considered in the borosilicate glass, since it is the critical component. For this simulation, the polycarbonate protection was neglected, since it does not add any rigidity to the system. The desired informations from these calculations are if the glass, the steel slabs and the screws will resist to the 10 bar absolute pressure (or 9 bar relative pressure) and if the boiling chamber will maintain sealed after this pressure is applied.

The borosilicate glass tube has 170 mm outer diameter, 200 mm length and 9 mm wall thickness. The stainless steel slabs have 300 mm diameter and 13 mm height, with two 5 mm grooves to place the glass and the polycarbonate tubes. All the holes in the slabs were filled to simplify the model. There will be six screws placed equally distributed around the test rig axis. They are made of regular structural steel and have 16 mm diameter. A picture of the model made in ANSYS Design Modeller can be seen in Fig. 3a. There is only one fourth of the model, because two symmetry planes were used to decrease the number of elements and, therefore, the computational time to perform the simulation. Fig. 3b shows the conditions and loads applied in the test rig.




(a) (b)

Figure 3. Static structural simulation (a) the test rig model, (b) the boundary conditions.

Notice the pretension in the bolt cut in half is only 2500 N, half of the whole value (5000 N). Those values were taken by the pressure applied on the slabs surfaces. Considering a 9 bar pressure, the resulting force would be approximately 18500 N, or about 3100 N per screw. Since the sealing is a highly non-linear material, it was decided to put 60% more bolt pretension to assure the sealing will withstand the boiling chamber pressure, which means 5000 N for each screw.

The results are available in Tab. 2. For the metallic materials, it is evaluated the Von Mises Equivalent Stress, while for the glass it is the Maximum Principal Stress.

Table 2. Calculated results for the mechanical loads

| Component | Maximum Stress [MPa] | Material Strength [MPa] | Approved? |
|---|---|---|---|
| ***Stainless Steel Slabs*** | 119 | 290 | YES |
| ***Borosilicate Glass Tube*** | 8.4 | 10.0 | YES |
| ***Steel Screws*** | 111 | 350 | YES |

According to the simulation results, all the components will withstand the pressure and the bolt pretension with safety. It closes the test rig critical dimensions: the borosilicate glass tube with 9 mm thickness (one of the thickest tubes found in the market), the stainless steel slabs with 13 mm thickness and six steel screws with 16mm diameter.

Although it seems the borosilicate glass is near to its limit, its ultimate strength in Tab. 1 already has a large safety coefficient, because of its sensitivity to cracks. Therefore, any part of the test rig will work close to its ultimate strength.

### 3.3 The Thermal Simulation

The objective of this calculation is to evaluate each part temperature and the boiling chamber heat loss. It will be observed if each component will withstand their component temperature. Moreover, it will be analyzed the test section and the thermocouples measures. It will also be validated the method used by Rao and Balakrishnan (2004) of calculating the heat flux using the 1-D Fourier Law equation and the temperatures acquired by the thermocouples.

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### 3.3.1 Boiling Chamber Heat Loss

Firstly, it was calculated the experimental rig without any thermal insulation, so it could be seen how much heat it loses naturally. Afterwards, the stone wool insulation was added to the model. Comparing with the primary calculation, it can be judged how much the thermal insulation helped to decrease the heat loss. In both simulations, the boundary conditions were extrapolated to the worst case. If it is numerically approved under these critical conditions, it will withstand the work conditions and the work fluid temperature control will be achievable.

The boundary conditions for the calculations were: boiling chamber faces at 150ºC; h = 20 $W.m^{-2}K^{-1}$ for all outer face in the model without insulation; h = 8 $W.m^{-2}K^{-1}$ for all outer face in the model with insulation. The inside temperature is approximately the ethanol saturation temperature at 10 bar absolute pressure. The heat transfer coefficient was different in each situation because the outer face temperature with insulation is much lower than without it, which means less heat transfer by convection.

Table 3 presents the heat flow in each external boundary for both models while Tab. 4 shows the maximum temperature each component reached in the model with stone wool cover.

Table 3. Heat flow through each boundary in each case and comparison

| Boundary | Total Heat Flow Without Insulation [W] | Total Heat Flow With Insulation [W] | Heat Loss Decrease After Using Insulation | Fraction of the Total Heat Loss (Model Without Insulation) |
|---|---|---|---|---|
| ***Upper Slab*** | 156.4 | 30.8 | 80.3% | 35% |
| ***Bottom Slab*** | 63.6 | 17.2 | 73.0% | 20% |
| ***Polycarbonate Tube*** | 28.4 | 18.8 | 33.8% | 22% |
| ***Screws*** | 48.4 | 20.0 | 58.7% | 23% |
| ***TOTAL HEAT LOSS*** | ***296,8*** | ***86,8*** | ***70,8%*** | ***100%*** |

Table 4. Components maximum calculated temperature

| Component | Maximum Temperature Reached [ºC] | Allowed Maximum Work Temperature [ºC] | Approved? |
|---|---|---|---|
| ***Borosilicate Glass Tube*** | 150 | 200 | YES |
| ***Polycarbonate Tube*** | 130 | 130 | YES |
| ***Viton® Sealing*** | 150 | 200 | YES |

The heat flow through the boiling chamber surface means the work fluid heat loss. Therefore, it must be as low as possible, so it is easier to keep it at the desired temperature. In the model without insulation, the greatest heat loss takes place through the upper steel slab, but also the other slab and the screws have significant feature in cooling the test rig.

The addition of thermal insulation in the test rig contributes significantly to control the work fluid temperature. Surely, studying better the dimensioning of the insulator it may achieve better results. However, it already shows that it is possible to decrease the boiling chamber heat loss using thermal insulators.

The polycarbonate presents a temperature equivalent to its allowed limit in a small region. It may be corrected increasing the stone wool layer between it and the steel slab, which is its greatest heat provider. All the other components were safely approved in the thermal simulation.

### 3.3.2 Test Section Analysis and Calculations

Finally, the funnel test section proposed by Rao and Balakrishnan (2004) was studied and their heat flux calculation method numerically validated. For this study, the model cut is shown in Fig. 6a and the test section cut in Fig. 6b, where the holes to place the thermocouples can be observed. The distance between two holes is 1mm and the distance between the hot surface and the first hole is 1.5 mm. The boundary conditions were chosen to approximate to the water boiling at critical heat flux (h = 45 $kW.m^{-2}.K^{-1}$) and to overestimate convection in the upper and bottom surfaces. The Teflon® side face is at 100ºC, the fluid saturation temperature, which is the same of the steel slab.

The 1-D Fourier Law, presented in Eq. (1), is used to calculate the heat flux through the hot surface. The differential equation is approximated as a ratio between the differences of two subsequent points (point *i* and *i-1*), as in Eq. (2). As there are four thermocouples aligned, it can be performed three calculations for the heat flux. Then, it is taken the

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average and it is defined as the heat flux through the hot surface. With this heat flux and the temperature acquired by the thermocouple at point 1, still using the 1-D Fourier Law, the hot surface temperature is calculated, as shown in Eq. (3).

$$q = k\frac{dT}{dx} \quad (1)$$

$$q = k\frac{T_i - T_{i-1}}{x_i - x_{i-1}} \quad (2)$$

$$T_{surface} = T_1 - \frac{q\,\Delta x}{k} \quad (3)$$

Assuring the thermocouples are measuring true temperatures means that the temperature acquired by it is the same temperature of the test section at that point. It can be different if the thermocouple is not well welded to the surface and if the hole where it is placed is too large. Therefore, in this simulation it is considered that the thermocouple is acquiring temperature of the air around it.


Figure 4. Test section thermal simulation (a) the test section set, (b) the test section model.

The Teflon® maximum temperature calculated was 182ºC, so it will withstand the thermal load. The results for the 1-D Fourier Law validation are presented in Tab. 5. The points mentioned in Tab. 5 are the ones shown in Fig. 6b.

Table 5. Results of the 1-D Fourier Law validation and the thermocouples acquisition with numerical simulation

| | True Temperature at the Point [ºC] | Temperature Acquired by the Thermocouple [ºC] | Temperature Difference ($T_i$-$T_{i-1}$) [ºC] | Heat Flux with 1-D Fourier Law [MW/m²] | Heat Flux from 1-D Fourier Law [MW/m²] | Surface Temperature from 1-D Fourier Law [ºC] |
|---|---|---|---|---|---|---|
| **Point 1** | 136 | 135 | -- | -- | 1,3 ± 0,1 | 130 ± 1 |
| **Point 2** | 139 | 138 | 3 | 1,2 | | |
| **Point 3** | 142 | 141 | 3 | 1,2 | | |
| **Point 4** | 146 | 145 | 4 | 1,6 | | |
| **Calculated Heat Flux with Numerical Simulation [MW/m²]** | | | | | 1,4 | -- |
| **Calculated Surface Temperature with Numerical Simulation [ºC]** | | | | | -- | 131 |

Therefore, the method used by Rao and Balakrishnan (2004) is numerically validated and the one-dimensional simplification can be used to calculate the hot surface temperature and the heat flux. Furthermore, in steady state, the temperatures the thermocouples will measure are very close to the true ones.

## 4. CONCLUSION

The current application desires a test rig capable to withstand high temperature and high pressure. Also, it is interesting to be able to visualize well the boiling. After reviewing the state of art of nucleate pool boiling test rigs, several ideas and concepts could be analyzed. To ease this study, all the information was gathered in a mind map, separating the components in six main groups: the boiling chamber, the pre-heating system, the condenser, the test section, the data acquisition system and the image acquisition system. The first four ones were emphasized because they present several solutions, unlike the last two ones.

Therefore, each component was chosen so they could comply with the project objective. For example, the boiling chamber will be made of borosilicate glass, which is an inert material and that resist high mechanical and thermal loads.

For the components that presented more than one feasible solution, the cheapest one was preferred. Thus, a cost-effective nucleate pool boiling test rig was generated and it can be seen in Fig. 2.

Since it will work at severe conditions, numerical simulation was performed to assure it will not failure after all the loads are applied. The results showed that, with the dimensions chosen for the test rig critical components, it will work safely at critical conditions. Moreover, the thermocouples acquisition and the one-dimensional Fourier Law approximation were validated to calculate the surface temperature and the heat flux, parameters used to plot the boiling curve.

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