Further development of Sand Bed Burner

Vidareutveckling av Sandbäddsbrännare

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Sammanfattning


Målet med examensarbetet är att förbättra nuvarande utrustning gällande fullständig förbränning över hela sandbäddsytan och lösa problemet med sjunkande gasflöde samt frysningen som uppstår på gasoltuberna enligt tidigare utprovning av studenter från Luleås tekniska högskola.

Sandbäddsbrännaren (SBB) fungerar på så vis att propangasen strömmar in i denna och fyller det tomma utrymmet under sandbädden innan gasen diffunderar genom bädden, där en förtändningsstation finns som sätter eld på gasen för att slutligen låta elden omsluka objektet som provas.

LPG befinner sig i vätskefas i flaskorna, men övergår till gasfas när den förbränns. Denna kräver tillgång till syre för en bättre förbränning. Denna gas övergår från vätskefas till gasfas och behöver då en stor mantelyta som tar upp mycket energi vilket resulterar i en bättre förångning som då hjälper gasen att övergå mellan faserna. Restprodukter vid fullständig förbränning är enbart vattenånga och koldioxid, dvs samma ämnen som i inandningsluften.


Resultatet visade på högre värmestrålningseffektivitet trots att flödet hade sänkts med ungefär 1/3 tack vare regulatorerna. I test 2 blev värmestrålningseffektiviteten 37 kW/m² samt i test 7 blev den 57 kW/m². På grund av ett så pass lågt flöde och större stålflaskor undveks till slut frysningen. Med en mindre sandfraktion tillsammans med fyra inlopp och tryckluft erhölls en jämnare förbränning över ytan.
Abstract

To determine whether a weapon system meets the requirements set for insensitivity, the system is getting exposed for special tests. One of these tests shows how the system reacts when it ends up in a fire. This test is called the "Fast Cook-Off (FCO) Test", called FCO-test, and performed with a Sand Bed Burner (SBB). According to primary testing provision, the fuel for this test is used of jet fuel such as Jet A-1. A project at Bofors Test Center (BTC) is in progress to use an alternative fuel of liquefied petroleum gas (LPG). This fuel is very advantageous compared to jet fuel in terms of environmental impact, work environment and testing costs.

The aim of this thesis is to improve the existing test equipment considering fire over the entire surface and solve the problems with dropped gas flow and freezing of gas bottles.

SBB works in the sense that the new petrol LPG streams into the SBB and expands in the free space below the sand bed before the gas will diffuse through the bed of sand and the fire engulfs the object.

LPG is a condensable gas that requires oxygen. LPG exceed from liquid to gas phase and needs a large lateral surface to take up more energy which results in better evaporation to the phase transfer. Reaction products from complete combustion of LPG are only water vapor and carbon dioxide, the same as in your exhaled air.

To solve these problems it was needed to change P11 composite bottles to P45 steel bottles to get a longer evaporation and larger lateral surface. Four flow inlets instead were used of one into SBB for a better stream in the free space under the sand bed. Propane regulators used to get a lower and more constant flow to avoid freezing. Compressed air connected to the SBB to get a mix between oxygen and LPG.

The result shows in higher heat radiation efficiency even though the flow was settled down to 1/3 with the new propane regulators. In test 2 the value was 37 kW/m² and in test 7 it was around 57 kW/m². Because of a smaller flow and bigger steel bottles the freezing disappeared. Smaller grain of sand together with four inlets and compressed air gave a more complete combustion.
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1. Introduction
This thesis is performed in mission of Bofors Test Center (BTC) in the course “Bachelor of Science in Mechanical Engineering”, MSGC17. The course is offered in the mechanical engineering program at the Faculty of Health, Natural and Engineering sciences at Karlstad University. This course is equivalent to 22.5 credits and is in the spring session year 2014. The guidance has been made both at Karlstad University and at the taskmaster BTC.

1.1 Background
A very important part of the development of new explosives technology weapons systems, such as artillery ammunition and warheads of missiles is aimed at making the system insensitive. This means that the system should react in a much less violent way than conventional systems do, when it ends up in hazardous situations such as fire, shelling, shrapnel hit or explosion in its immediate vicinity.

To determine whether a weapon system meets the requirements set for insensitivity, the system is getting exposed for special tests. One of these tests shows how the system reacts when it ends up in a fire. This test is called the "Fast Cook-off Test" and denotes FCO. According to primary testing provision, the fuel for this test is the jet fuel Jet A-1. A project at BTC is now in progress to use an alternative fuel of propane gas (LPG). This fuel is very advantageous compared to jet fuel in terms of environmental impact, work environment and testing costs. In this thesis LPG will be used.

In spring 2013, a thesis has been done at BTC by two students from fire engineer program at Luleå Technical University (LTU). The aim of this thesis was to develop and through testing, verify test equipment (sand bed burner), an inert test object (probe), a method of measurement (temperature and heat radiation) and an analysis of the heating processes in fire with jet fuel and propane gas. The test equipment shall be sufficient patient to heating the objects of size about 0.8 × 0.3 m. Production of test equipment and inert test object takes place at BTCs workshop. ”The result of their work was very successful and it has been presented of BTC in autumn 2013 at international working group meetings and seminars in the Netherlands, USA and Australia. However, it turned out that this test equipment, which in the context of the thesis at the technical university in Luleå only would be a prototype who needs to be optimized to function as intended.

1.2 Purpose and problem formulations
The purpose of this thesis is to improve the existing test equipment considering fire over the entire surface and solve the problem with the gas admission.

1.3 Goal
The goal is that after the thesis has a finished burner in terms of temperature- and heat radiation characteristics that has the same performance as the combustion of Jet A-1.

There are two primarily main problems that need to be solved:

• Problems with the dropped gas flow and freezing on gas bottles

• Problems with incomplete combustion over the SBB’s entire surface.

The work should be completed by 21 May 2014.
1.4 Limitation
Study problems considering only one SBB. The time is not enough to study same problems at more burners that are coupled together to get a bigger surface.

1.5 Nomenclature

LPG = Liquefied Petroleum Gas
SBB = Sand Bed Burner
FCO = Fast Cook Off
\( \dot{q} \) = Heat release rate of the fire
\( \dot{m}^\ast \) = Mass loss rate = mean flow divided with surface area on SBB \( \frac{kg}{m^2s} \) (Evers and Möllerström 2013).
\( \chi = 0.9 \) = Combustion efficiency (Evers and Möllerström 2013).
\( \Delta H_c = 46 \) = Heat of combustion [MJ/kg] (Evers and Möllerström 2013).
\( A_{SBB} = 1.15 \) = Area of the SBB \( [m^2] \)
u = Velocity in the flame centerline \( [m/s] \)
z = Height over sand bed to the adiabatic surface probe
Re = Reynolds number
d = diameter of adiabatic surface probe \( [m] \)
C = Constants, see table 4.
A = Constants, see table 4.
n = Constants, see table 4.
\( T_g \) = Mean gas temperature \( [K] \)
\( T_r \) = Radiation temperature \( [K] \)
\( T_{AST} \) = Mean surface temperature \( [K] \)
\( \sigma = 5.67 \times 10^{-8} \) [W/m\(^2\)K\(^4\)] (Evers and Möllerström 2013).
\( \varepsilon = 0.9 \) = Emissivity (Evers and Möllerström 2013).
h\(_c\) = Heat transfer coefficient \( [W/m^2K] \)
\( \dot{q}^\ast_{\text{inc}} \) = Incident radiation efficiency \( [W/m^2] \)
2 Method

The methods that are used in this degree project are chosen with the assistance of knowledge from the earlier course Integrated product development. This is done to simplify and get at better structure of the project.

2.1 Project planning

Milestones were fixed points in the project to achieve the desired results. These have been exposed at the end of each project phase to mark the finishing of a specific phase (Eriksson & Lilliesköld 2004). Quite many milestones were chosen to have a good control through the whole process and to have sub targets to go for. Most important milestones are concept description, concept generation and report at the end of the project. Breakdown and choice of the phases was done with knowledge from earlier courses.

Gates was placed at important stages of the project that must be approved, in this case by the taskmaster who ordered the work, before next phase can continue (Eriksson & Lilliesköld 2004). Most important elements were considered as project plan, requirements specification and concept choice.

A project model was constructed to divide the project into smaller parts and thus get an overview about the project phase, milestones, gates and who was responsible for each step (Eriksson & Lilliesköld 2004).

Work Breakdown Structure (WBS) was very useful for the planning of the project, see appendix 2. This is a type of planning that was necessary to do. Breaking down all project components were made to identify the tasks in a better way and to make time-schedule easier. WBS was made using the computer software Microsoft Visio (Eriksson & Lilliesköld 2004).

A Gantt chart was made in Microsoft Project, see appendix 4. This was used as the "official" timeline because it was easy to see how all the phases are interrelated. Graphic illustration of the project given by Gantt to get a great overview in terms of how long each stage was and how they depend on each other (Eriksson & Lilliesköld 2004).

A background description of why the project was started and what had to be solved was written based on the mission statement from BTC, see appendix 6.

Organisation around the project was described. Supervisors from BTC and KAU and also the taskmaster are listed with their names, functions in the project, telephone and e-mail. This is done for all too easily communicate with each other (Eriksson & Lilliesköld 2004).

Risk analysis was an important tool to see which suggested arrangement that could be used if some accident happened. It was also a useful tool to rank all the risks and see which of them who was worst. A brainstorming session was started where all risks were noted for a limited time. A risk matrix was made where all risks are listed and thereafter rated in terms of probability and consequence. Scale 1-5, there 5 was the worst scenario. Then multiplication of both terms was made to see which the worst risk was (Eriksson & Lilliesköld 2004).
2.2 Research

- Studied all the photos and videos from the tests that were done in the degree project from last year.
- Read about FCO test to understand the goal of the test.
- Investigated how the SBB was assembled, how it worked and how it was used.

A quite big part in the beginning of the project was research. This determined the main part of the design future costs (Johannesson et al. 2004) and in this stage it was only small resources to worked with.

A meeting with both supervisors and the taskmaster was organized at Karlstad University to take advantage of more detailed information about the project. In the meeting the BTC supervisor described a more thorough description of the project. BTC showed how the project was conceived and what it was about.

2.2.1 Insensitive munitions

Definition for insensitive munitions are “Munitions which reliably fulfill their performance, readiness and operational requirements on demand and which minimize the probability of inadvertent initiation and severity of subsequent collateral damage to weapon platforms, logistic systems and personnel when subjected to selected accidental and combat threats” (AOP-39 Edition 3 2010, Annex A-1).

It started in Vietnam 1967 on USS Forrestal with a crew of about 5000 people. Fully loaded airplanes with munitions were ready for a mission when an airplane accidentally fired a loaded rocket into the fuel tank of another airplane, and the disaster started. Like a domino effect explosions were spread to all of the other aircrafts. This catastrophe resulted in 134 deaths, 161 injured, 21 aircraft totally destroyed and 39 aircraft damaged (Raymond L Beauregard 2011).

After this disaster The Aircraft Carrier Review Panel decided to develop a remote-controlled firefighting system, improve life-save equipment, more training to survive in case of fire and development of insensitive munitions (Raymond L Beauregard 2011).

There are six tests included in insensitive munitions. FCO test is used in this thesis:

- Fast Cook-Off
- Slow Cook-Off
- Bullet Impact
- Fragment Impact
- Shaped Charge Jet Impact
- Sympathetic Reaction

(AOP 39E Edition 3 2010, page 7)
2.2.2 Fast Cook-Off

Fast cook off is a test where munitions are completely engulfed in a hydrocarbon fuel fire, see figure 1, such as that resulting from an aircraft crash on a ship or road transport accident.

The flames should be fuel rich and heat transfers that reach the object should be 90% radiative (STANAG 4240 Edition 2 2003, page 2). To know that the object not is placed in a cooler part of the hearth, the orientation will fulfill the requirements for an average temperature of the flame not less than 800 °C and lasting for about twenty minutes. The flame need to reach 550 °C before the first 30 seconds (STANAG 4240 Edition 2 2003, Annex A-2).

![Figure 1. The burner during a FCO-test](image)

2.2.3 Sand Bed Burner

BTC has a LPG system with ten interlocked bottles withholding propane that are coupled to one each solenoid valve, see figure 2. The valves do it possible to open and close the bottles and let the LPG stream in special hoses made for propane, i.e. LPG hoses. Thereafter the gas continues inside the SBB where gas will diffuse through a bed of sand to get combustion with flames that are surrounded around the munitions (papers Toreheim session 5A).

In order to get the gas to torch when it comes to the top of the sand surface, a pre-torch station is used. This station included a separate LPG bottle that stream in a LPG hose into a pipe filled with a lot of small holes and with two spark plugs attached at each end of the pipe. The spark plug ignites the gas.

![Figure 2. Solenoid valves to open the bottles](image)
2.2.4 LPG vs. Jet – A1

LPG is a condensable gas that saves a lot of energy and will fit with plenty of volume on a relatively small area\(^1\).

Propane has very high energy content; 1kg of propane corresponds to 12.8 kWh\(^2\). If a complete combustion will be made, the temperature of the blue flame is 1900 °C\(^3\). LPG bottles can be able to deliver a certain quantity of LPG per hour without extra help; a thumb rule is 1 kg/h\(^4\). For example if a stove consumes 2.5 kg/h fuel should three bottles be connected in series. AGA If the bottles had too large outflow it was a risk that the liquid from the LPG bottles not boiled and been cooled down and it became frost formation at the outside of the bottle which results in less pressure\(^5\). Eventually the bottle is unpressurised even though there are liquid left. Propane requires oxygen for combustion\(^6\). If 1 kg of LPG will be burned it need 12 m\(^3\) air\(^7\).

The propane gas is also used for agriculture and within the household for cooking and heating (Energigas Sverige 2014).

LPG is together with natural gas the cleanest fossil energy source and also has lower carbon emissions than either coal or oil (Energigas Sverige 2014).

Reaction products from complete combustion of LPG are only water vapor and carbon dioxide, the same as in your exhaled air (Kosan Gas AB 2014).

The soot combines with oxygen in the flame and dashes off as CO\(_2\).

The reaction formula for complete combustion of LPG\(^8\):

\[
C_3H_8 + 5 O_2 \rightarrow 4 H_20 + 3 CO_2
\]

Propane + oxygen \rightarrow Water + carbon dioxide.

It has high utilization factor and is a flexible energy source. It is free from lead and poisons (Kosan Gas AB 2014).

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\(^1\) Lööfs gasol, interviewed in 14th of March 2014
\(^2\) AGA in Sandviken, interviewed in 17th of April 2014
\(^3\) Lööfs gasol, interviewed in 14th of March 2014
\(^4\) AGA in Sandviken, interviewed in 17th of April 2014
\(^5\) AGA in Sandviken, interviewed in 17th of April 2014
\(^6\) Lööfs gasol, interviewed in 14th of March 2014
\(^7\) AGA in Örebro, interviewed in 16th of April 2014
\(^8\) AGA in Örebro, interviewed in 16th of April 2014
Advantages with LPG instead of Jet-A1:

- Lower impact on environment
- Lower fuel costs
- Shorter set-up times
- Shorter run time period
- Better working environment for the staff.

(Papers IMEMTS 2010, page 4)

2.2.5 Standards

Two standards were relevant to study for this project. These standards were about insensitive munitions and FCO-test. A summary from these standards, see 2.2.5.1.

2.2.5.1 STANAG 4240 and AOP-39

The flames should be fuel rich and heat transfers that reach the object should be 90% radiative. The hearth shall be sufficiently large to allow minimum 1m free space on each side of the object. It should be designed in order to acquire a flame that has enough volume to swallow the whole object during the test.

The amount of fuel that should be used to maintain a fully evolved fire for a defined cycle has to be 150% of the calculated reaction time. The object has to be centered within the area of the hearth and its principal axis horizontal. The object’s lower surface has to be sufficiently high above the combustible area to full combustion under the object to be permitted.

To know that the object not is placed in a cooler part of the hearth, the orientation will fulfill the requirements for an average temperature of the flame not less than 800 °C. The flame need to reach 550 °C before the first 30 seconds. At least four thermocouples are required that shall be oriented front, back, left and right. Data must be recorded with maximum five seconds interval (0.2 Hz).

FCO-tests are not recommended to be performed in rainy conditions because of heating problems. Neither if wind speed exceeds 2.8 m/s on the basis of circumstances that prevents the flames to engulf the object.

2.3 Budget

The budget work started with a meeting to get a closer look at the existing SBB and the gas system to know which components may be used.

It continued with a search for components at internet and had both e-mail and telephone contact with a lot of different gas companies nearby. Components that has been searched for are flow meter, preheater, agitator and evaporator there every component should fulfill the requirements for LPG.

2.4 Product specification

A product specification was made to give everyone a unanimous view on the project’s goal (Johannesson et al. 2004).

The specification will be updated along the project with new knowledge emerged.
2.4.1 Olsson’s criteria matrix

Functional requirements described the functionality of the desired system, which usually consists of some kind of calculation and given specific inputs. Non-functional requirements describe performance of the system, in this case for SBB and LPG system. Safeties, maintainability, user-friendly are some of the requirements for the system (Johannesson et al. 2004).

The document has been used by the performer, supervisor and taskmaster for feedback, adjustments and approval. These persons have to approve it before next step in the project started. This was important because the work proceeds by following these criteria.

First of all a table was made there the life cycle phase’s design, manufacture, maintains and the aspects environment, process, humanity and economy were connected with each other, see appendix 5. The matrix had a simple lay out where the rows consist of life cycle phases and the columns described aspects to be considered in each life cycle phase.

Thereafter, a new table was made, and the criteria numbers and the cells were inserted in the table. A short description of what every cell means and if there are functions/limits and wish/requirements were also inserted.

All of the life cycle phases and criteria did not seem to be relevant for this mission and was thus left empty.

2.4.2 Quality Function Deployment

A Quality Function Deployment (QFD), see appendix 12, was done to achieve higher quality of the burner by designed functions according to the BTCs requirements. QFD was a tool used to connect BTC requirements and product characteristics with each other so it was possible to improve the goals. The selected BTC needs from criteria matrix are listed together with the weighting of the importance of the needs in the scale of 1-5. Then the measurable characteristics of the product (design criteria) were determined. By linking BTC’s needs and design criteria to each other, a value judgment was made to tell how strong the relationship between them was. Then it was able to see which characteristics that was most important and what needed to accomplish (Johannesson et al. 2004).

2.5 Concept generation

Concept generation gave a description of the product’s functionality and appearance which resulted in a number of conceptual product solutions. A systematic concept generation process was used to include all possible ideas by using generic tools. The process was based on BTC’s needs and requirements.

A brainstorming session started the concept generation, see table 1. “Systematical and rational methods” were used as tools (Johannesson et al. 2004) to find solutions to the identified sub-functions.

Discussions with supervisors from BTC were performed in intervals to get ideas and proposal for continued work.
Several companies that are concentrated upon gas were contacted there the main problems was presented. Threw discussion with them, different solutions for these problems was found, see table 1.

The company that showed most interest was Lööfs gasol in Karlstad. A meeting was held at their office to show more in detail what the problems were.

After contact with fluid technical lecturer Hans Löfgren further ideas noted and some of them were same as Lööfs gasol. Main purpose at the meeting was to get help with a fluid program to see which of the brainstorming alternative that can be sorted or hopefully to get further alternatives.

Possible solutions were assembled after all information was obtained. All tests were concept generations. There were many ideas that could solve the main problems, but it was impossible to know which of them that gave best results. Threw testing it was decided which concept generations that was most appropriate to the concept choice process.

All the solutions became a collection of many more or less valuable proposals to each relevant main problem. All the tests were concept generations, see 2.5.2.1-7.

Later an elimination matrix was designed to sort out some of the proposal before testing.

Table 1. Brainstorming session

<table>
<thead>
<tr>
<th>Number</th>
<th>Incomplete combustion</th>
<th>Number</th>
<th>freezing of gas flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bigger grain of sand</td>
<td>17</td>
<td>Preheater</td>
</tr>
<tr>
<td>2</td>
<td>Smaller grain of sand</td>
<td>18</td>
<td>Different gastubes</td>
</tr>
<tr>
<td>3</td>
<td>Angled inlets</td>
<td>19</td>
<td>Different material in inlet pipe</td>
</tr>
<tr>
<td>4</td>
<td>Straight inlets</td>
<td>20</td>
<td>Tubes that are coupled together</td>
</tr>
<tr>
<td>5</td>
<td>Thickness of sand</td>
<td>21</td>
<td>Bigger bottles</td>
</tr>
<tr>
<td>6</td>
<td>Triangular SBB</td>
<td>22</td>
<td>Heat bottles (tarpaulin, spiro pipe and fan)</td>
</tr>
<tr>
<td>7</td>
<td>Circular SBB</td>
<td>23</td>
<td>Propan regulator</td>
</tr>
<tr>
<td>8</td>
<td>Different gasflow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Amount of propane in the LPG</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Agitator</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Steel reinforced pipe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Sand to the bottom</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Pipe construction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Vulcanizing tape</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Wool fiber and nai wire</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Air pressure with compressor</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Explanations solutions from the brainstorming session, se appendix 7.

2.5.1 Manufacture of prototype
The SBB was improved in the workshop KVU with four inlets. To get gas flow from all four sides of the SBB it was drilled four holes in the outer steel frame. The steel frame that was placed inside the SBB needed to be cut into four pieces, where the new holes were drilled where the frame was not in the way of the inlet holes. Steel pipes had to be weld around each hole where the gas and compressed air hoses should be attached. Inner diameters of the pipes were as big as the inlet holes, see appendix 10.
Manifolds was built by components for downsized dimensioning because the rubber hose from the propane bottles had an inside diameter of 6 mm and inlet into SBB was 30 mm wide.

Two inlets for compressed air was manufactured as simple as possible. Steel pipes with a given diameter, see appendix 10, were welded on the SBB and then a 90 degree pipe was threaded, see figure 3. The compressor was connected into a socket with two outlets that the air were allocated, see figure 4.
Figure 5 showed the current design before the improvements. The new design has been made there it will be four inlets instead that goes into each side of the SBB. On two of the manifolds that connect into the SBB it was place for two LPG bottles at each manifold, see figure 6, and on the other two manifolds there are jacks to connect three bottles at each manifold, see figure 7. These ten bottles was scattered at four manifolds to flow from four different sides.

**Figure 5.** Design of inlets from last year (Evers and Möllerström 2013).

**Figure 6.** Two-way manifold

**Figure 7.** Three-way manifold
Two separate inlets for compressed air to get better potential to mix it with the LPG were attached. Diameter of the hole in the SBB and inner diameter of the compressed air pipe was 9 mm, see appendix 10.

Inner steel frame used to stabilize the design and to hold up the sand bed net. Two holes were drilled through the steel frame to get compressed air into the SBB. The design has 6 separate inlets instead of one, four inlets for LPG and two for compressed air. Total height of SBB is 170 mm and the sand layer was about 100 mm, see appendix 10. The isolated water hoses were changed to steel pipe design that made it much more sustainable to resist fire. Standard components were used as much as possible to get a cheap and simple design. Material for inner and outer steel frame was structural steel due to the price it was strong enough. Cheapest steel pipes used consider no strength needed.

2.5.2 Testing
The tests were relatively small and without any risks in terms of explosions because no sharp objects were tested. The tests showed in which order they should be performed, see 2.5.2.1-7. The tests started with the solution that generate as few changes and cheapest as possible to the existing design. There was a need for necessary equipment like:

- Smaller and bigger sand fraction,
- Bigger bottles to the new LPG system,
- Manufacture of new inlets,
- Tractors to set windscreens and at least one employed that helped to monitor and prepare the tests.

The proposed scheme for the tests to complete combustion was to see difference between fractions of sand, four angled inlets, sand to the bottom of the SBB, agitator and a circular SBB. Scheme to avoid freezing was to compare difference between steel bottle and composite bottle, change P11 composite bottle to a P45 steel bottle, steel reinforced hose and use a preheater. These schemes were changed as long as the tests were made and new information and ideas appeared. Unfortunately the weather was not good enough at any of these tests. It was 10 °C and cloudy, except from test 4 where it was 16 °C and sunny.

An adiabatic test probe was used instead of munitions and was placed 200 mm over the sand bed. It was used in every tests and has a simple cylindrical geometry with thermocouples that measure gas- and surface temperature in four positions.
2.5.2.1 Test 1
The first test was only a function test to make sure the equipment was in order. The water hoses melted but were repaired before the next test. A preliminary burner for increased temperature inside the container was prepared before the next test. A fan used that blow hot air into a thick pipe fixed in the container roof to warm up the LPG system; see figure 8. The usual 4-8 mm gravel tested together with the four new inlets. It was relatively calm wind.

![Figure 8](image)

**Figure 8.** Device to increase temperature around the LPG system.

2.5.2.2 Test 2
A test was made to investigate the new design for four LPG inlets into the SBB, see figure 9. Street gravel with sizes 4-8 mm was used again. The wind was about 4 m/s. Only one windscreen to avoid gust was used.

![Figure 9](image)

**Figure 9.** Picture over the new steel pipe design
2.5.2.3 Test 3
Same test as above but two windscreens to reduce wind speed.

2.5.2.4 Test 4
Same test as above but three windscreens to reduce wind speed were used. The wind speed was already low and with the windscreens it was almost calm. The bottles were not preheated through the fan due to the relatively high ambient temperature.

2.5.2.5 Test 5
Three windscreens to reduce wind speed were used. Fraction of sand with sizes 8-11 mm was tested. Wind speed was the same as in test 2-3.

2.5.2.6 Test 6
Three windscreens to reduce wind speed were used. Fraction of sand with sizes 2-4 mm was tested. Wind speed was the same as in tests 2-3.

2.5.2.7 Test 7
Adjusted the regulators to 1.1 bar in the bottles and used 2.0 bar compressed air.

Preheated bottles and LPG hoses was warmed up to 17 °C before the test.
2.6 Concept choice
The elimination phase started when all the developed concepts were finished. In the elimination matrix there are question formulations like: does the concept solve the main problem, satisfy requirements, realizable, within margin of expenditure, secure and ergonomic, relevant for the company, sufficient information listed together with solution options and decided which concepts was approved. The purpose of the matrix was to systematically eliminate concepts that cannot meet all the requirements of product specification and the question formulations above. The solutions that satisfied all the requirements are further analyzed in the concept selection process (Johannesson et al. 2004).

After the elimination matrixes, table 2 and 3, two decision matrixes were made for each problem. These solutions judged how good they satisfied the most important requirements compared to the given reference. In the elimination matrix every brainstorming idea was analyzed. For further information about the requirements, see appendix 5.

Table 2. Elimination matrix for complete combustion, see appendix 7

<table>
<thead>
<tr>
<th>Solution number</th>
<th>Solves main problem</th>
<th>Satisfy all requirements</th>
<th>Realizable</th>
<th>Within margin of expenditure</th>
<th>Secure and ergonomic</th>
<th>Relevant for the company</th>
<th>Sufficient information</th>
<th>Decision</th>
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</tr>
</tbody>
</table>
3. Theory

The equations below used to calculate heat radiation efficiency for every test. It was done to compare heat radiation efficiency for LPG and Jet-A1 to see if the performance for LPG was good enough, see appendix 9 (Evers & Möllerström 2013).

\[ \dot{q} = A \dot{m}^* \chi \Delta H_c \]  
\[ u = 6.8 \left( \frac{z}{q^{2/5}} \right)^{1/2} \dot{q}^{1/5} \]  
\[ Re = \frac{1}{1.13 \times 10^{-9}} \ast \frac{u \cdot d}{\tau_{gas}^{1.67}} \]  
\[ h_c = A \ast C \ast \frac{T_{g,92}^{0.92} - 1.67 n + \theta_{g,90}}{d^{1-n}} \]  
\[ \dot{q}_{inc}^* = \sigma T_{AST}^4 \frac{h_c}{\varepsilon} (T_g - T_{AST}) \]  
\[ \dot{q}_{inc}^* = \sigma T_r^4 \rightarrow T_r = \sqrt[4]{\frac{\dot{q}_{inc}^*}{\sigma}} \]

Table 4. Constants that will be used in equation (4) depending on Reynolds number (Evers & Möllerström 2013)

| \textbf{Re}_{df} & \textbf{\Gamma} & \textbf{C} & \textbf{n} & \textbf{A} [\text{SI units}] |
|------------------|-----------------|--------|--------|-----------------|
| 0.4-4            | (0.45 - 4.5)*10^{-9} | 0.989  | 0.330  | 0.110           |
| 4-40             | (4.5 - 45)*10^{-9}  | 0.911  | 0.385  | 0.341           |
| 40-4 000         | (45 - 4500)*10^{-9} | 0.683  | 0.466  | 1.81            |
| 4 000-40 000     | (4.5 - 45)*10^{-6}  | 0.193  | 0.618  | 41.4            |
| 40 000-400 000   | (45 - 450)*10^{-6}  | 0.0266 | 0.805  | 1950            |
4. Results

4.1 Behavior of LPG
Freezing occurs constantly because of cold gas. Less LPG left in the bottles leads to freezing is more visible. It is always LPG left on the bottom of the bottles due to evaporation cannot keep up the consumption rate (charge more LPG than it has time to evaporate / consumed). The flow dropped when vaporization capacity drop. A thumb rule for LPG is that it can vaporize 1kg gas / hour\(^9\).

The pressure in the gas reservoir varies with the ambient temperature. Flow rates vary greatly depending on the ambient temperature and the filling ratio for the bottles\(^10\).

Composite bottles loose pressure much easier and hypothermia goes faster than with steel bottles. Bigger steel bottles manage to vaporize itself longer time than smaller composite bottles\(^11\).

To set SBB at an elevation to get the LPG to flow upstream before it flowed into the SBB prevent that the unwanted liquefied phase, that not has been evaporated, more easily remain in the hoses and so on get a cleaner combustion\(^12\).

A larger lateral surface at the bottles allows the gas to take up more energy which results in better vaporization. If less gas is left in the bottles it will be a smaller lateral surface that will try to take up energy and thereby lower speed of evaporation. To obtain a high flow a higher heat and energy requires in transition phase liquid to gas which leads to a cooling the mantle surface. According to AGA Sandviken\(^13\) the air of the liquid is condensed and the moisture settles on the metal surface which causes frosting.

The distance between LPG system and SBB is a hypothermic process, especially in bad weather conditions. If LPG cools down too much along this distance there is bigger risk for LPG to return to the liquid phase again. The liquid phase does not vaporize and if this phase stream into the SBB it will be incomplete combustion\(^14\).

4.1.1 Budget
To keep the cost as low as possible no flow meter will be bought. Another way of measured gas flow, see 4.4

Existing LPG system was upgraded from P11 composite bottles to bigger P45 steel bottles from BSIAB AB in Karlskoga. The number represent amount of LPG in unit kg. It was advantages because bottles with steel material was cheaper than small composite bottles and it also need more time to cooling which results in less freezing.

Pipe design for all inlets into SBB was considered to be most durable over long time.

To get an overview over the budget, see appendix 11.

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9 Lööfs gasol, interviewed in 14th of March 2014
10 Jan Eriksson workshop KVU, interviewed 6th of May 2014
11 Lööfs gasol, interviewed in 6th of May 2014
12 Jan Eriksson workshop KVU, interviewed 6th of May 2014
13 AGA in Sandviken, interviewed in 17th of April 2014
14 AGA in Sandviken, interviewed in 17th of April 2014
4.2 Project plan
To ensure the project was delivered in time are these critical incidents and their associated arrangement’s importance to regard, see appendix 1.

The work has been performed in a front loaded process and had continuous follow-up with supervisors and taskmaster.

During the project new problems have been discovered and new questions have arisen. The taskmaster’s requirements and preferences changed a little over time but the problem formulations was still the same.

The first goal was to get such complete combustion as possible to remove the soot from the sand surface. Some soot was desirable to resemble jet fuel as much as possible. The goal was instead to get an even distribution of a thin layer sooting over the sand bed.

4.3 Product specification
Results of the product specification were requirement specification, Olsson's criteria matrix and QFD.

The specification was used throughout the whole work as a template in the process to get the best possible burner that BTC requires.

The functional and non-functional requirements were requirements that BTC has chosen.

The criteria that was specified in Olsson's criteria matrix, see appendix 5, was made for simplifying the final results of the requirement specification. Criteria matrix was made of totally 21 criteria of which 13 was requirements and 6 requests. Two of the criteria were not relevant. When the requirement specification was completed it was presented for the supervisors on BTC and KAU to get confirmation that the project was performed in the right direction. A single change was made and the project was satisfied for BTC.

The main requirements on the product were avoid freezing in the gas bottles and obtain complete combustion over the entire surface. Other important requirements were use of LPG as fuel, use standard components, manufacture a mobile burner, easy to maintain, secure burner and low total cost for the burner.
4.4. Testing and Verification

The cheapest solution, but not as exact as a flow meter, was to get the gas flow from LPG bottles and scale one bottle and note how much weight the bottle lost at every 30 seconds and then multiply with amount of bottles i.e. 10 bottles, see appendix 8 for diagrams and figure 10 for picture. Average flows was calculated, by taking start-weight on one bottle and note the weight of the same bottle after the test and then divided with number of seconds the test was performed.

![Figure 10. Measurement of flow](image)

![Image](image)

The adiabatic test probe measured temperatures with sample rate 5 Hz

4.4.1 Test 1

Because of the melted hoses the LPG could not stream into the SBB and engulf the object in the correct way and therefore the gas temperature declined and reduced according to the chart, see appendix 8. Regard the sand bed it was a quite thick layer of almost even sooting, see figure 11. No heat radiation efficiency calculation was made for this test.

Due to wind beam the temperature measurements were not trust worthy. The peaks were about 1000 °C which was great but when the adiabatic probe were not exposed to the flames was the lowest value 130 °C, see appendix 8. The test lasted in 4 minutes.
The flows from the LPG bottles are uniformly constant at 0.12 kg/sec, see appendix 8, but much higher than the degree project from last year (Evers and Möllerström 2013). It was higher flow compared to last year because it is 4 inlets instead of 1. More inlets results in a greater gas flow\textsuperscript{15}. The combustion was more scattered over the entire surface with four inlets which indicated a more even distribution of LPG, see figure 11.

To make a FCO-test with the same qualifications every time the pressure has to be equal. It will not be equal when the external temperature changes which leads to modified pressure. 27 °C is optimal in the area where the bottles stand in order to get a better evaporation\textsuperscript{16}.

\textbf{Figure 11. Combustion test 1}

\textbf{4.4.2 Verifications}

The biggest change that was made after test 1 was to use steel pipe design instead of water hoses protected with isolation for the LPG gas distribution. The water hoses melted down and are also containing 30% Dietylhexylftalat which is one substance from EU: s candidate list over particularly hazardous substances.

Steel pipe design was a very simple and effective solution that satisfied its purpose. This design was used in all of the tests. When the SBB will be used with sharp object instead of the adiabatic test probe it will cause explosions. To avoid breaking as little material as possible it was necessary to keep the material away from the heat and explosion area. This design included four similar pieces assembled with steel pipes in varied lengths depending on which SBB inlet relevant pipe will connect to. At each inlet there is one 90° angle pipe welded.

\textsuperscript{15} AGA in Örebro, interviewed in 16th of April 2014
\textsuperscript{16} Jan Eriksson workshop KVU, interviewed 6th of May 2014
LPG is very sensitive and the pressure varied a lot in terms of occupancy level and ambient temperature, see 4.1. In the cold weather it was problem with low pressure. If the ambient temperature is below 6 °C it is almost impossible to get a complete combustion of LPG. To prevent this as much as possible the bottles had to be heated. A simple and cheap alternative was to do like test 1, but place the Spiro pipe at the bottom of the container. The heat raises and the most important area in the bottles to heat was the top of the bottles where the outlets are located.

4.4.3 Test 2
The investigation of the new steel pipe design gave a positive result. No external damaged. Aside from the upper right corner it was evenly spread combustion but with partial dark sooting, see figure 12.

Mean flow 0.14 kg/sec with a highest top at 0.2 kg/sec thereafter constant dipped 0.12 kg/sec there the test stopped, see appendix 8.

Mean surface temperature 628 °C
Mean gas temperature 619 °C

This was the only test where surface temperatures were higher than gas temperatures, see appendix 8. Probably depended on which interval the mean temperatures were chosen to be calculated.

It was also the only test where Reynolds number exceed 4000 and get other values to equation (4), see table 4.
Incident radiation 37539 W/m²
Radiation temperature 629 °C

Figure 12. Combustion from test 2

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17 Jan Eriksson workshop KVU, interviewed 6th of May 2014
18 Jan Eriksson workshop KVU, interviewed 6th of May 2014
4.4.4 Test 3
After an analysis of temperatures it was decided to use three windscreens. It was uneven sooting with partial dark spots, see figure 13.

Mean flow was 0.11 kg/sec with a highest top at 0.13 kg/sec which was constant in 210 sec before it dipped to 0.10 kg/sec, see appendix 8.

Mean surface temperature 675 °C
Mean gas temperature 739 °C
Incident radiation 44535 W/m²
Radiation temperature 668 °C

![Figure 13. Combustion from test 3](image)

4.4.5 Test 4
Average flow was 0.12 kg/s with a highest top at 0.18 kg/sec and constantly dipped to 0.12 kg/sec where test 4 stopped, see appendix 8. Aside from the same corner as earlier tests it was even combustion with dark sooting over the surface, see figure 14.

Mean surface temperature 716 °C
Mean gas temperature 807 °C
Incident radiation 52410 W/m²
Radiation temperature 708 °C

It was the best weather conditions at this test which resulted in highest gas temperature.

![Figure 14. Combustion from test 4](image)
4.4.6 Test 5
Mean flow was 0.10 kg/s with a highest top at 0.16 kg/sec and constantly dipped to 0.10 kg/sec where test 5 stopped, see appendix 8. The sooting area looked like a rectangle and were thus not evenly combusted, see figure 15.

Mean surface temperature 684 °C
Mean gas temperature 713 °C

Incident radiation 46961 W/m²
Radiation temperature 681 °C

![Figure 15. Combustion from test 5](image)

4.4.7 Test 6
Mean flow was 0.09 kg/s with a highest top at 0.16 kg/sec and constantly dipped to 0.10 kg/sec where test 6 stopped, see appendix 8. Aside from the same corner as earlier it was even combustion and much less dark sooting over the surface, see figure 16.

Mean surface temperature 713 °C
Mean gas temperature 718 °C

Incident radiation 53491 W/m²
Radiation temperature 713 °C

![Figure 16. Combustion from test 6](image)
### 4.4.8 Verifications

It had to be increased temperature around the LPG system to prevent the gas phase to return to liquid phase when it streams from the LPG bottles into the SBB\(^9\), see 4.1.

In order to increase the temperature more, these actions can be made:

- Keep the hose into the container to be heated up when it was cold outside. This works like a mini vaporizer that keeps the temperature in the hoses for a longer time and reduces risks for hypothermia. A solution was to hang hoses on top of the bottles to minimize the risk for the liquid to follow the stream all the way into the SBB\(^{20}\).
- Insulate the hoses lying on the ground with heat resistant insulation, and cover the solenoid valves.
- Pressure regulators intended for propane should be purchased to adjust the pressure and thereby reduce the high flow.
- By supply compressed air through a pair of separate inlets in SBB the combustion was improved. A mix between LPG and oxygen get reduced soot because of a more complete combustion, higher gas temperature and reduce freezing due to less flow\(^{21}\). By increase the combustion a larger blue flame was obtained which lead to a higher gas temp and smaller gas flow received.

### 4.4.9 Test 7

Propane regulators adjusted to 1.1 bar from the LPG bottles and compressed air of 2.0 bar.

Mean flow at 0.033 kg/sec which was constant all the time, see appendix 8.

It was even combustion with much less dark sooting over the surface than the other tests, see figure 17. The only difference between test 6 and 7 was pressure of the compressed air.

All the values were best in this test although a flow that was 1/3 of rest of the tests. An adjusted low pressure with the regulators needed to get a constant flow with no freezing.

Mean surface temperature 729 °C
Mean gas temperature 757 °C

Incident radiation 56594 W/m\(^2\)
Radiation temperature 727 °C

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\(^{19}\) Jan Eriksson workshop KVU, interviewed 6th of May 2014
\(^{20}\) Jan Eriksson workshop KVU, interviewed 6th of May 2014
\(^{21}\) Lööfs gasol, interviewed in 6th of May 2014
4.5 Concept choice

4.5.1 Delete selected proposals
Evaporators were not used because they had no capacity to evaporate enough volume. An alternate solution was to put the spiro pipe at the floor in the container instead of hang the spiro pipe in the container roof. It was the gas in the bottom of the bottles that had to be heated up because the freezing area of the gas bottles started in the bottom.\(^{22}\)

Worked at the same way as ”sand to the bottom” alternative. There was no idea to try with less sand because gas takes the easiest way from limited spaces.\(^ {23}\) With less sand the gas would found the easy way more easily and therefore not been spread all over the surface.

The time to build a triangular SBB was not enough. This idea was not optimal due to it will be hard to center the object on a good way for the fire to engulf the object.

The amount propane in the gas is not possible to change after the bottles are delivered. Gas needs between 2-10\% propane, if it includes more or less than the interval it cannot be any fire.\(^ {24}\)

The agitator was not considered relevant because it was built several inlets instead that works at the same way and it is also a cheaper proposal.

Steel reinforced pipes were put aside for the pipe designs because of the pipe designs get more stability and more robust.

Sand to the bottom may work but it was no time to test it. In this test it was available to try more thickness of sand because no net was needed.

Vulcanizing tape and the other solution with wool fiber and naį wire worked last year but was not as safe as the steel pipe design when it became exposed for fire for a long time. The tape was twined around the water hoses (which are not going to be legal in the future), see 4.4.2.

Bottles coupled together as a package solution was not available to do with single bottles.\(^ {25}\) The only alternative to solve this is to buy package solutions from the beginning.

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\(^ {22}\) Jan Eriksson workshop KVU, interviewed 6th of May 2014
\(^ {23}\) Lööfs gasol, interviewed in 14th of March 2014
\(^ {24}\) Lööfs gasol, interviewed in 14th of March 2014
\(^ {25}\) AGA in Örebro, interviewed in 16th of April 2014
4.5.2 Decision matrix

The significance of solutions can be found in appendix 7. Decision matrix that solved the problem with freezing LPG bottles, see table 5. Decision matrix that solved the problem with uncompleted combustion, see table 6.

Table 5. Decision matrix to avoid freezing

<table>
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<th>Criteria</th>
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Table 6. Decision matrix to complete combustion

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<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Mobile burner</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
</tr>
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Best solutions for the two main problems were the decisions that get a Yes. These solutions are also best considering all the tests.
5. Discussion

The work has been carried out according to the product development processes that have been followed through the entire process. All the steps were carefully followed. This method is widely known and proven product development process and well-used in engineering works. The tests comprise a large part of this thesis as required validations and vary appearance of the burner to find the right combinations to satisfy the goals. This work has been carried out almost all the time at BTC where a lot of necessary information received from the employed.

One part in this kind of tests is that every test needs same conditions every time to be able to compare them with each other. Biggest distractions that affect the results are wind gusts. The wind speeds have to basically be calm. Tests performed in windy circumstances results in less heating than requested. Even if the wind is less than 2.8 m/s which is the maximum wind speed, see 2.2.5, it affects gas- and surface temperature too much and makes it hard to reach mean temperatures over 800 °C. To get a fair comparison between the tests, the gas flow needs to be constant and with same values. Too big differences in gas flow do not provide fair conditions for heat radiation efficiency and should therefore be avoided.

One problem with the FCO-test with a SBB was that the heating is uneven allocated. The flames do not engulf the object as desired. Temperature differences between highest and lowest can be about 200 °C. This problem arises probably because of the windy weather.

These tests were performed with an adiabatic surface temperature probe i.e. an inert object that can not explode. For every improved arrangement it needs to analyze the manufactured improvement because of sharp objects will be used and it will smash some parts. Lowest cost at all the used components with respect to enough strength used to get a cheap SBB as possible. Only standard dimensions for all the details was used and as few parts as possible to get a cheaper design because it will break down quite often. This burner fulfilled given requirements, see appendix 5.

Improvements that have been made should resist exploding objects. The SBB had to be upgraded considering inert/sharp object will be used and thus had to construct robust improvements with high strength.

Three broken solenoid valve was detected before the last test when ten propane regulators was installed (manometers on these three regulators showed false values and solenoid valves were cold compared to the other ones). The triangle in the same corner on all tests has not accomplished complete combustion exists, probably because three solenoid valves were broken. With three broken solenoid valves means three LPG bottles without any gas flow. Unfortunately two of three bottles were coupled to the same two-way manifold which means the inlet at the back of the SBB did not have any function.

It became irregular LPG flows without the regulators because of variation in pressure. For example one test had 0.20 kg/sec flow and dropped during the whole test. Next test it was a flow about 0.13 kg/sec that was quite constant instead. The finished design that has been manufactured in this thesis satisfies requirement specifications and posted goals.
6. Conclusion

Results of this degree project are considered to be good and the problems have been solved. The heat radiation efficiency was 56594 W/m$^2$ and the tests with Jet A-1 from last year were given heat radiation efficiency for about 55 kw/m$^2$ (Evers & Möllerström 2013) and thus have accomplished the goal with at least the same performance as Jet A-1. The performance for LPG can be even higher with an optimal mix between LPG and air, this result in a higher and more even temperature$^{26}$. More inlets together with smaller grain of sand and compressed air resulted in an even sooting over the entire surface. A much lower and regulated flow with propane regulators instead of open bottles for full flow gave a constant gas flow. Reduced flow resulted in freezing gas bottles, see figure 18 and read more about in in 2.2.4. To avoid freezing a change of LPG bottles from P11 composite to P45 steel improved to better evaporation of liquid. Preheat container was difficult to say if it worked or not. With a more advanced preheating burner a better temperature into the container could be achieved. Last test was the only one that showed that the problem formulations have been solved. Grain of sand gave big differences in result. 2-4 mm grain of sand had better heat radiation than the other sizes.

![Figure 18](image)

Figure 18. Freezing gas bottles

At calm weather conditions the average gas temperature was over 800 °C between chosen intervals in test 4. In test 7 it was more tops around 1000 °C instead of test 4, but because of the wind it was too many low measured temperatures in test 7. If it was same wind speed in test 7 as in test 4 it should theoretically be higher mean temperatures in test 7 even thus the regulators were adjusted to 1.1 bar (1/3 of the mean flow from test 4).

---

$^{26}$ Lööfs gasol, interviewed in 14th of March 2014
6.1 Further development

Further tests needs to be done to adjust propane regulators and make the pressure of compressed air more optimal. It would be necessary to do tests to try if it is any other height than 20 cm that gives best temperature.

Evaporator cabinet is an alternative to get same ambient temperature around the bottles whatever the weather condition is. This solution is only for bottles coupled in package or extra-large bottles with a weight on 184 kg. One disadvantage with this solution is the price that was estimated to 50 000-100 000 SEK\textsuperscript{27}.

A pipe isolation to the gas hoses at the ground could warm them up easier instead of twin a wall insulation or fire blanket around them.

Several bottles coupled together with a switcher between the bottles that switch the bottle when the pressure drops. Through the use of packet coupling the bottles cooperates with each other in a better way. A problem with this is that it is very complicated to try couple switch single bottles into a packet with each other, but it is available to buy packages from scratch.

By using parallel connection it turns all bottles to help each other to take out the last gas from the bottom of the bottles and results in a better evaporation\textsuperscript{28}.

Place the bottles in a water-bath to get a higher temperature and thus better evaporation.

Fill the bottles with LPG more often to have a bigger lateral surface.

Build a raised wall as keep the flames straighter in windy conditions.

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\textsuperscript{27} AGA in Sandviken, interviewed in 17th of April 2014

\textsuperscript{28} AGA in Sandviken, interviewed in 17th of April 2014
Acknowledgement

Special thanks are dedicated to Jon Toreheim, Alf Prytz and Kent Connedahl with crew at BTC for all the help answers around this project and during the tests.

Also thanks to the supervisor at Karlstad University, Jan Eriksson in the workshop with crew and Leif Holm at Lööfs gasol for all LPG help with new ideas to try and for design help to improve the existing SBB.
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Evers, B. & Möllerström, P. (2013). *Fast cook-off test with a sand bed burner*. Diss. Luleå: Department of Civil, Environmental and Natural resources engineering, Luleå University of Technology. In-Text Citation: (Evers & Möllerström 2013)


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In text citation: (Kosan Gas AB 2014)

Energigas Sverige (2014). Gasol och miljön. (Electronic)
In text citation: (Energigas Sverige 2014)

Energigas Sverige (2014). Användningsområden. (Electronic)
In text citation: (Energigas Sverige 2014)
Appendix 1. Project plan

This thesis is performed in mission of Bofors Test Center in the course “Bachelor of Science in Mechanical Engineering”, MSGC17. The course is offered in mechanical engineering program at the Faculty of Health, Natural and Engineering sciences at Karlstad University. This course is equivalent to 22.5 credits and is in the spring session year 2014. The handling has been made both at Karlstad University and at the taskmaster Bofors Test Center.

Introduction

A very important part of the development of new explosives technology weapon systems, such as artillery ammunition and warheads of missiles, aimed at making the system insensitive. This means that the system should react in a much less violent way than conventional systems do, when it ends up in hazardous situations such as fire, shelling, shrapnel hit or explosion in its immediate vicinity.

To determine whether a weapon system meets the requirements set for insensitivity, the system is getting exposed for special tests. One of these tests shows how the system reacts when it ends up in a fire. This test is called the "Fast Cook-off Test" and denotes FCO. According to primary testing provision, the fuel for this test is used of jet fuel such as Jet A-1. A project at Bofors Test Center (BTC) is now in progress to use an alternative fuel of propane gas (LPG). This fuel is very advantageous compared to jet fuel in terms of environmental impact, work environment and testing costs.

In spring 2013, a thesis has been done at BTC by two students from fire engineer program at Luleå Technical University (LTU). The aim of this thesis was to "develop and through testing, verify a test equipment (sand bed burner) , an inert test object (probe) , a method of measurement (temperature and heat radiation) and an analysis of the heating processes in fire with jet fuel and propane gas. The test equipment shall be sufficient patient to heating the objects of sizes about 0.8 × 0.3 m. Production of test equipment and inert test object takes place at BTC’s workshop.” The result of their work was very successful and it has been presented of BTC in autumn 2013 at international working group meetings and seminars in the Netherlands, USA and Australia. However, it turned out that this test equipment (sand bed burner), which in the context of the thesis at the technical university in Luleå only would be a prototype who need to be optimized to function as intended.

Goal

The purpose of this thesis is to improve the existing test equipment considering fire over the entire surface and solve the problem with the gas admission.

The goal is that after project completions have a finished burner in terms of temperature- and heat radiation characteristics that has the same performance as the combustion of Jet A-1.

There are two primarily main problems that need to be solved:

- Problems with the gas admission to the burner.
- Problems with incomplete combustion of the sand bed burner’s entire surface.

The work should be completed by 23 May 2014.
### Taskmaster

Bofors Test Center, 691 52 Karlskoga, Bofors Skjutfält 201 tfn 0586 840 01

### Project model

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Comments on schedule and resource plan

Dates for testing are not selected yet because it can be chosen pretty close to the intended date. Testing and verification can vary a lot in time that depends on whether you can find a good solution quickly or not. Research is an important part in this project. The research is planned to do continuous over the whole project. It is important to consider that the thesis runs at half speed to v.14. Holidays have not been taken into consideration.

Risk judgement

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Document handling

A project on its learning has been started to make it easier for the supervisor to follow the mission. All of the documents will be saved on its learning. Backup will occur every day. A backup will be made at the end of every single day.

The electronic platform its learning will be used for document handling and for communication to the supervisor at Karlstad University.
Appendix 2. Work Breakdown Structure
## Appendix 3. Pert chart

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Appendix 6. Mission statement

Beskrivning
En mycket viktig del av utvecklingen av nya explosivvänstekniska vapensystem, som t.ex. artilleriammunition och verkansdelar till missiler, inriktas på att göra systemet lågkänsligt. Detta innebär att systemet skall reagera på ett avsevärt mindre våldsamt sätt än vad konventionella system gör, då det hamnar i vådasituationer som exempelvis brand, beskjutning, splittertråff eller explosion i dess omedelbara närhet.


Under våren 2013 har ett examensarbete utförts vid BTC av två studenter från brandingenjörsprogrammet vid Luleå Tekniska Universitet (LTU). Syftet med detta examensarbete var att ”ta fram och genom provning verifiera en provningsutrustning (sandbäddsbrännare), ett inert provningsobjekt (mätprob), en mätmetod (temperatur och värmestrålning) och en analys av uppvärmningsförloppen vid brand med flygbränsle respektive propangas. Provningsutrustningen skall vara tillräcklig för uppvärmning av objekt av storlek ca 0,8 × 0,3 m. Tillverkning av provningsutrustning och inert provningsobjekt sker vid BTCs verkstad.” Resultatet av deras arbete blev mycket lyckat och det har av BTC under hösten 2013 presenterats vid internationella arbetsgruppmöten och symposier i Nederländerna, USA och Australien. Dock visade det sig att denna provningsutrustning (sandbäddsbrännaren), som i ramen för examensarbetet vid LTU endast skulle vara en prototyp, behöver optimeras för att fungera som tänkt.

Det är framförallt två huvudproblem som behöver löstras:

- Problem med gastillförseln till anläggningen.
- Problem med att det inte brinner över hela ytan.

Syfte
Syftet med detta examensarbete är att förbättra befintlig provningsutrustning avseende brand över hela ytan samt lösa problemet med gastillförseln. Målet är att efter examensarbetet ha en färdig anläggning som vad gäller temperatur- och värmestrålningsegenskaper uppvisar samma prestanda som vid förbränning av Jet A-1.
**Genomförande**

Examensarbetet kan förslagsvis utföras i följande steg:

**Introduktion**
- Handledare från BTC informerar om BTC och beskriver uppgiften detaljerat. Examensarbetaren presenterar sig själv och beskriver grovt hur han tänkt lösa uppgiften. Studiebesök för att bese befintlig propangasanläggning vid BTC och BTC:s verkstad för tillverkning av utrustning.

**Informationssökning**
- Examensarbetaren söker, med stöd av handledare från BTC och Karlstads Universitet, efter den grundinformation som behövs. Detta kan handla om standarder, ritningsunderlag, leverantörer av gasolutrustning, läroböcker i strömningsteknik etc. Beträffande standarder ges riktlinjerna för denna provning i STANAG 4240 ed.2 och AOP-39 ed.3.

**Planering**
- En planering över hur projektet ska bedrivas ska tas fram. Detta arbete kan med fördel utföras i MS Project.

**Budgetarbete**
- En budget för projektet ska utarbetas. Denna ska godkännas av handledaren från BTC.

**Konstruktion**
- Design och konstruktion inklusive ritningsunderlag till provningsutrustningen ska tas fram. Dessa underlag bör finnas tillhandaa efter informationssökningsfasen. Provningsutrustningen ska ritas upp i 3D CAD. Eftersom BTC inte kan tillhandahålla sådana system utförs detta arbete vid KaU. Rtningsunderlaget ägs efter avslutat projekt av KaU men BTC äger full rätt att använda detta.

Styrande för konstruktionen är att så många komponenter som möjligt är av standardtyp. Detta i syfte att hålla kostnader nere samt för att enkelt kunna reparera systemet då detta slås sönder vid eventuella våldsamma reaktioner hos skarpa provningsobjekt. Vidare skall bränslet som skall användas vara propangas och dessutom skall systemet vara mobilt och ej behöva tillståndskrav från myndigheter (Länsstyrelse, kommun, MSB). Konstruktionen skall uppfylla kravspecifikationen enligt STANAG 4240 ed.2 och AOP-39 ed.3.

**Analys**
- En analys av tänkbara konstruktioner skall göras utifrån ett strömningstekniskt och/eller värmtekniskt perspektiv. Finns lämpliga verktyg för modellering och simulering vid KaU kan sådana med fördel användas.

**Materielframtagning och tillverkning**
- Den materiel som behövs ska tas fram och tillverkning ska utföras. Hur det utförs bestäms till stor del av examensarbetaren men tillverkning sker lämpligen vid BTC:s verkstad. Viktigt är att budgeten hålls, att standarder följs och att provningsutrustningen uppvisar tillfredsställande kvalitet.
**Provning och verifiering**

- Provningsutrustningen ska provas och vid behov ändras och omprovas samt slutligen verifieras genom skarp provning. Måtmetoder beskrivna i tidigare utfört examensarbete vid LTU skall användas. Provning och verifiering kommer att utföras på BTC med stöd av handledare från BTC.

**Projektuppföljning**

- Såväl projektplan som budget ska följas upp under projektets gång för att slutligen summeras och analyseras.

**Avrapportering**

- En teknisk rapport över arbetet ska skrivas (gärna på engelska). Den ska även innehålla all dokumentation som inhämtats under arbetets gång samt allt ritäningsunderlag. Avrapporteringen ska även ske muntligt med stöd av ett presentationsunderlag i MS PowerPoint. Kopior härpå skall överlämnas till BTC.

BTC skall äga full rätt att presentera materialet som framkommit i detta examensarbete vid sådana tillfällen som företaget finner vara av intresse.

**Handledare vid BTC**

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**Handledare vid KaU**

Göran Karlsson

Tel: 054-700 18 52

Mobil: 070-533 03 35

Email: goran.karlsson@kau.se

**Tidsåtgång**

Uppdragets omfattning förordrar en examensarbetare på 22,5 poäng dvs. 22,5 veckor.

Arbetet är rekommenderat att bedrivas på halv- och helfart under ca 4 månader.

**Tidsplan**

20 januari – 3 juni 2014.

Redovisning av arbetet skall ske på KaU 3 juni och på BTC 10 juni 2014.

**Plats**

BTC eller KaU, beroende på vilket moment som utförs.

**Övrigt**

Ersättning utgår enligt SAAB:s avtal för examensarbete.
Appendix 7. Explanations for solution proposal before elimination

Number 1: Change to bigger (8-11 mm) sand fraction and keep existing grid.

Number 2: Change to smaller (2-4 mm) sand fraction and use a denser grid.

Number 3: Angled inlets at four sides to make gas turbulence inside the SBB.

Number 4: Straight inlets at four sides to make gas turbulence inside the SBB.

Number 5: Fill the SBB with more sand to get a greater height on the sand bed.

Number 6: Manufacture a SBB that has triangular geometry.

Number 7: Manufacture a SBB that has circular geometry. With a circular burner the gas “bounces” at the sides.

Number 8: A lower gas flow if the current has to fast flow rate and collide on the other side in the burner which results in uneven flowing.

Number 9: Try to adjust the amount of propane in LPG. Between 2-10% propane for combustion.

Number 10: A sort of mixer inside the burner that help the gas to make turbulence inside the SBB.

Number 11: Use a longer steel reinforced hose instead of rubber hoses to avoid choking and liquefaction.

Number 12: Fill all the volume in the SBB with sand and have manifolds at the bottom with a couple of hollow hoses.

Number 13: Use steel pipes instead of the existing water hose as inlets in the SBB. It will be safer and more robust for a longer time.

Number 14: Use the existing water hose and isolate it with vulcanizing tape to protect the hose from high temperatures.

Number 15: Use the existing water hose and isolate it with wool fiber and nai wire to keep it in place to protect the hose from high temperatures.

Number 16: Do two separate inlets for compressed air with a compressor.

Number 17: Install a preheater on every LPG bottle to warm up the LPG.

Number 18: Choose steel bottles instead of composite.

Number 19: Same as number 11.

Number 20: To use series connection with all the bottles it takes same amount of gas from every bottle.

Number 21: Bigger bottles makes the cooling take longer time. Upgrade gas bottles from P11 to P45.

Number 22: Warm up the container with a tarpaulin, spiro pipe and a fan to avoid liquefaction in the red LPG hoses.

Number 23: Propane regulator to get a moderately large flow.
Appendix 8. Diagrams for testing

Test 1

**Flow rate - 10 tubes**

**°C**

- T2 (down)
- T4 (up)

**C**

- T1 (up)
- T3 (down)
Test 3

Flow (kg/sec)

°C

K 1 (left) °C
K 2 (right) °C
K 3 (down) °C
K 4 (up) °C

°C

K 5 (up) °C
K 6 (right) °C
K 7 (down) °C
K 8 (left) °C
Test 4

Flow (kg/sec)

°C

K 1 (left)
K 2 (right)
K 4 (up)
K 4 (up)

°C

K 5 (up)
K 6 (right)
K 7 (down)
K 8 (left)
Appendix 9. Calculations for heat radiations efficiency

Test 2

\[ \dot{q} = A_{sbb} \dot{m} \chi \Delta H_c = 1.15 \times 0.122 \times 0.9 \times 46.0 = 5,808 \frac{MW}{m^2} = 5808 \frac{kW}{m^2} \]

\[ u = 6.8 \left( \frac{Z}{q^2/5} \right)^{1/2} \dot{q}^{1/5} = 6.8 \left( \frac{0.2}{5808^{2/5}} \right)^{1/2} 5808^{1/5} = 3.04 m/s \]

\[ Re = \frac{1}{1.13 \times 10^{-6}} \times \frac{u d}{T_{gas}^{1.67}} \frac{1}{1.13 \times 10^{-9}} \times \frac{3.04 + 0.11}{892^{1.67}} = 4469 \]

Values for A, C and n are given from table 4. A=41, 4, C=0,193 and n=0.618. These values are inserted in Equation (4).

\[ h_c = A \times C \times \frac{T_{gas}^{0.92-1.67n} \times u^0}{d^{a-n}} = 41.4 \times 0.193 \times \frac{892^{(0.92-1.67 \times 0.618)} \times 3.04^{0.618}}{0.110^{(1-0.618)}} = 17,24 \frac{W}{m^2K} \]

\[ \dot{q}_{inc}^* = \sigma T_{A}\dot{T} \times \frac{h_c}{\varepsilon} (T_{gas} - T_{A}) = 5.67 \times 10^{-8} \times 901^4 - \frac{17.24}{0.9} (892 - 901) = 37539 \frac{W}{m^2} \]

\[ \dot{q}_{inc}^* = \sigma T_r^4 \rightarrow T_r = \sqrt{\frac{\dot{q}_{inc}^*}{\sigma}} = \sqrt{\frac{37539}{5.67 \times 10^{-8}}} = 902 K = 629 ^\circ C \]

Test 3

\[ \dot{q} = A_{sbb} \dot{m} \chi \Delta H_c = 1.15 \times 0.081 \times 0.9 \times 46.0 = 4850 \frac{kW}{m^2} \]

\[ u = 6.8 \left( \frac{Z}{q^2/5} \right)^{1/2} \dot{q}^{1/5} = 6.8 \left( \frac{0.2}{4850^{2/5}} \right)^{1/2} 4850^{1/5} = 3.04 m/s \]

\[ Re = \frac{1}{1.13 \times 10^{-6}} \times \frac{u d}{T_{gas}^{1.67}} \frac{1}{1.13 \times 10^{-9}} \times \frac{3.04 + 0.11}{1011^{1.67}} = 3626 \]

Values for A, C and n are given from table 4. A=1, 81, C=0,683 and n=0.466. These values are inserted in Equation (4).

\[ h_c = A \times C \times \frac{T_{gas}^{0.92-1.67n} \times u^0}{d^{a-n}} = 1.81 \times 0.683 \times \frac{892^{(0.92-1.67 \times 0.466)} \times 3.04^{0.466}}{0.110^{(1-0.466)}} = 18.0 \frac{W}{m^2K} \]

\[ \dot{q}_{inc}^* = \sigma T_{A}\dot{T} \times \frac{h_c}{\varepsilon} (T_{gas} - T_{A}) = 5.67 \times 10^{-8} \times 948^4 - \frac{18.0}{0.9} (1011 - 948) = 44535 \frac{W}{m^2} \]

\[ \dot{q}_{inc}^* = \sigma T_r^4 \rightarrow T_r = \sqrt{\frac{\dot{q}_{inc}^*}{\sigma}} = \sqrt{\frac{44535}{5.67 \times 10^{-8}}} = 941 K = 668 ^\circ C \]
\[ \dot{q} = A \cdot \dot{m} \cdot \chi \Delta H_c = 1.15 \times 0.107 \times 0.9 \times 46.0 = 5092 \text{ kW/m}^2 \]

\[ u = 6.8 \left( \frac{Z}{\dot{q}^{2/5}} \right)^{1/2} \dot{q}^{1/5} = 6.8 \left( \frac{0.2}{5092 \text{ kw}^{2/5}} \right)^{1/2} 5092^{1/5} = 3.04 \text{ m/s} \]

\[ Re = \frac{1}{1.13 \times 10^{-9}} \times \frac{u \cdot d}{T_{gas}^{1.67}} = \frac{1.13 \times 10^{-9}}{1.13 \times 10^{-9}} \times \frac{3.04 + 0.11}{1080 \text{ kg/m}^3} = 3247 \]

Values for A, C and n are given from table 4. A=1.81, C=0.683 and n=0.466. These values are inserted in Equation (4).

\[ h_c = A \times C \times \frac{\tau_{gas}^{0.92 - 1.67n}}{d^{1-n}} = 1.81 \times 0.683 \times 1080^{0.92 - 1.67 \cdot 0.466} \cdot 3.04 \cdot 0.466 = 18.16 \frac{W}{m^2 \cdot K} \]

\[ \dot{q}_{inc}^* = \frac{\sigma T_{AST}^4}{\varepsilon} \left( \frac{h_c}{T_{gas} - T_{AST}} \right) = 5.67 \times 10^{-8} \times 989^4 - \frac{18.16}{0.9} (1080 - 989) = 52410 \frac{W}{m^2} \]

\[ \dot{q}_{inc}^* = \frac{\sigma T_r^4}{\varepsilon} \rightarrow T_r = \sqrt[4]{\frac{\dot{q}_{inc}^*}{\sigma}} = \sqrt[4]{\frac{52410}{5.67 \times 10^{-8}}} = 981 \text{ K} = 708 \text{ °C} \]

Test 5

\[ \dot{q} = A \cdot \dot{m} \cdot \chi \Delta H_c = 1.15 \times 0.084 \times 0.9 \times 46.0 = 4016 \text{ kW/m}^2 \]

\[ u = 6.8 \left( \frac{Z}{\dot{q}^{2/5}} \right)^{1/2} \dot{q}^{1/5} = 6.8 \left( \frac{0.2}{4016^{2/5}} \right)^{1/2} 4016^{1/5} = 3.04 \text{ m/s} \]

\[ Re = \frac{1}{1.13 \times 10^{-9}} \times \frac{u \cdot d}{T_{gas}^{1.67}} = \frac{1.13 \times 10^{-9}}{1.13 \times 10^{-9}} \times \frac{3.04 + 0.11}{987 \text{ kg/m}^3} = 3774 \]

Values for A, C and n are given from table 4. A=1.81, C=0.683 and n=0.466. These values are inserted in Equation (4).

\[ h_c = A \times C \times \frac{\tau_{gas}^{0.92 - 1.67n}}{d^{1-n}} = 1.81 \times 0.683 \times 987^{0.92 - 1.67 \cdot 0.466} \cdot 3.04 \cdot 0.466 = 17.93 \frac{W}{m^2 \cdot K} \]

\[ \dot{q}_{inc}^* = \frac{\sigma T_{AST}^4}{\varepsilon} \left( \frac{h_c}{T_{gas} - T_{AST}} \right) = 5.67 \times 10^{-8} \times 957^4 - \frac{18.0}{0.9} (987 - 957) = 46961 \frac{W}{m^2} \]

\[ \dot{q}_{inc}^* = \frac{\sigma T_r^4}{\varepsilon} \rightarrow T_r = \sqrt[4]{\frac{\dot{q}_{inc}^*}{\sigma}} = \sqrt[4]{\frac{46961}{5.67 \times 10^{-8}}} = 954 \text{ K} = 681 \text{ °C} \]
$\dot{q} = A_{sbh} \dot{m} \Delta H_c = 1.15 \times 0.080 \times 0.9 \times 46.0 = 3809 \text{ kW/m}^2$

$u = 6.8 \left( \frac{Z}{Q^2/5} \right)^{1/2} \dot{q}^{1/5} = 6.8 \left( \frac{0.2}{3809^{2/5}} \right)^{1/2} 3809^{1/5} = 3.04 \text{ m/s}$

$Re = \frac{1}{1.13 \times 10^{-9}} \frac{u*d}{T_{gas}^{1.67}} = \frac{1}{1.13 \times 10^{-9}} \frac{3.04 \times 0.11}{991^{1.67}} = 3749$

Values for $A$, $C$ and $n$ are given from table 4. $A=1.81$, $C=0.683$ and $n=0.466$. These values are inserted in Equation (4).

$h_c = A \times C \times \frac{T_{gas}^{0.92-1.67n+u_{3n}}}{d^{1-n}} = 1.81 \times 0.683 \frac{991^{0.92-1.67 \times 0.466} \times 3.04 \times 0.466}{0.110^{1-0.466}} = 17.94 \text{ W/m}^2 K$

$\dot{q}_{inc}^* = \sigma T_{AST}^4 - \frac{h_c}{\epsilon} (T_{gas} - T_{AST}) = 5.67 \times 10^{-8} \times 986^4 - \frac{18.0}{0.9} (991 - 986) = 53491 \text{ W/m}^2$

$\dot{q}_{inc}^* = \sigma T_r^4 \Rightarrow T_r = \sqrt[4]{\frac{\dot{q}_{inc}^*}{\sigma}} = \sqrt[4]{\frac{53491}{5.67 \times 10^{-8}}} = 986 \text{ K} = 713 \text{ °C}$

Test 7

$\dot{q} = A_{sbh} \dot{m} \Delta H_c = 1.15 \times 0.029 \times 0.9 \times 46.0 = 1366 \text{ kW/m}^2$

$u = 6.8 \left( \frac{Z}{Q^2/5} \right)^{1/2} \dot{q}^{1/5} = 6.8 \left( \frac{0.2}{1366^{2/5}} \right)^{1/2} 1366^{1/5} = 3.04 \text{ m/s}$

$Re = \frac{1}{1.13 \times 10^{-9}} \frac{u*d}{T_{gas}^{1.67}} = \frac{1}{1.13 \times 10^{-9}} \frac{3.04 \times 0.11}{1001^{1.67}} = 3516$

Values for $A$, $C$ and $n$ are given from table 4. $A=1.81$, $C=0.683$ and $n=0.466$. These values are inserted in Equation (4).

$h_c = A \times C \times \frac{T_{gas}^{0.92-1.67n+u_{3n}}}{d^{1-n}} = 1.81 \times 0.683 \frac{1030^{0.92-1.67 \times 0.466} \times 3.04 \times 0.466}{0.110^{1-0.466}} = 18.04 \text{ W/m}^2 K$

$\dot{q}_{inc}^* = \sigma T_{AST}^4 - \frac{h_c}{\epsilon} (T_{gas} - T_{AST}) = 5.67 \times 10^{-8} \times 1002^4 - \frac{18.0}{0.9} (1030 - 1002) = 56594 \text{ W/m}^2$

$\dot{q}_{inc}^* = \sigma T_r^4 \Rightarrow T_r = \sqrt[4]{\frac{\dot{q}_{inc}^*}{\sigma}} = \sqrt[4]{\frac{56594}{5.67 \times 10^{-8}}} = 1000 \text{ K} = 727 \text{ °C}$
pipe Ø12x100, t=1,5
S355JR

Designed by: Adam Jansson
Model name: PIPES_AIRHOLES
Date: 2014-05-13
Scale: 1:1

KARLSTADS UNIVERSITET
Drawing no. 006
## Appendix 11. Budget

<table>
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<th>Product</th>
<th>Quantity</th>
<th>Company</th>
<th>Price (SEK)</th>
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<td>Sand fraction 2-4 mm</td>
<td>300 kg</td>
<td>Gelleråsen grus</td>
<td>550</td>
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<td>Sand fraction 8-11 mm</td>
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<td>Gelleråsen grus</td>
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<tr>
<td>Regulator propane 4 bar</td>
<td>10 pieces</td>
<td>Lööfs gasol</td>
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<td>Fire blanket</td>
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### Material manifolds

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<td>Cutting rings</td>
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<tr>
<td>Screw nuts</td>
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<tr>
<td>Angled pipes 90 °</td>
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### Construction compressed air

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<td>Screw nuts</td>
<td>4 pieces</td>
<td>Nikar</td>
<td>100</td>
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### Labor cost

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<td>Staff</td>
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## Appendix 12. Quality Function Development

### Quality Characteristics
(a.k.a. "Functional Requirements" or "Hows")

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<tr>
<th>Row #</th>
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<th>Weight / Importance</th>
<th>Demanded Quality</th>
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<td>1</td>
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<td>11.4</td>
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<td>9.1</td>
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<td>Low cost facility</td>
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<td>3</td>
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<td>10</td>
<td>3</td>
<td>11.4</td>
<td>5.0</td>
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### Direction of Improvement
Minimize (▼), Maximize (▲), or Target (x)

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<th>Weight</th>
<th>Assemble</th>
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