

Induction Furnace Lining and Industrial Vibrator Design

Compaction of Dry Refractory Material Using Pneumatic Vibrator

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Bachelor's Thesis

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<p>Abstract</p> <p>This project was carried out in accordance with İDEAL Foundry Technologies to design a better vibrator which is used to install refractory for coreless type induction furnaces. The third party Allied Minerals U.S. has taken a big role on testing manufactured prototype. Current vibrators were not sufficient to cover all needs when lining induction furnace.</p> <p>Project has started by evaluating existing preparation methods/machines and making a failure mode and effect analysis. Student aimed on avoid problems found out after this preliminary research. New design of existing machine, and complete new design of pistons were made while this project. In other respects material selection and machining issues were clarified with the sense of available production resources.</p> <p>Summerized, all the technical points were achieved while thesis and mass production has started according to designed system. Allied Mineral U.S. has signed (manufacturing) supplier agreement with İDEAL Foundry Technologies for this production.</p> <p>Next step of this project will be aimed on compaction ratio analyse of refractory mass under certain vibration frequencies.</p>			
<p>Keywords compaction, vibration, pneumatic vibrator, pneumatic piston, refractory, refractory lining, refractory ramming, induction furnace.</p>			

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1 INTRODUCTION

In the foundries, melting is done by furnaces. Even though there are several type of furnaces electric arc furnace and induction furnace are the most commonly in use nowadays. They are chosen by the alloy system quantities produced. In this report induction furnaces will be mentioned which are used for ferrous materials. An iron foundry can use electric arc, induction or cupola furnace. Cupola furnaces are not in use often because this old technology is not as efficient and environment friendly as induction furnace. They emit too much dust and other pollutants. Induction heating method is much cleaner and easy to control compared to other methods. In this process, electromagnetic induction coils generate “Foucault currents” with conducting object (metal). Frequency of current used depends on the size of the object and material type.

Induction coils must be protected from the melted metal by isolation material called refractory. ASTM C71 defines refractories as "non-metallic materials having those chemical and physical properties that make them applicable for structures or as components of systems that are exposed to environments above 538 °C." They must be resistant to thermal shock and have ranges of thermal conductivity. Alumina, silica, magnesia are the most common refractory materials used. Refractory materials could be shaped or unshaped (monolithic refractories). Dry vibration operation is generally used in induction furnace lining that are monolithic. This dry powder must be compacted with homogenous density. Because lining material's lifetime, depends on this fact.

Refractory ramming process has been done by pneumatic vibrators operated manually so far. Doing this process by hand cannot guarantee homogenous ramming which will cause shorter lifetime of refractory. Besides manual method takes much longer time when installing the refractory.

This project was carried out in accordance with IDEAL Foundry Technologies to design a better vibrator which is used to install refractory for coreless type induction furnaces. The third party Allied Minerals U.S. has taken a big role on testing manufactured prototype. Current vibrators were not sufficient to cover all needs when lining induction furnace.

1.1 INDUCTION MELTING FURNACE

Induction furnace is the basic foundry machine to melt material by induction heating. It has an electric inductor coil which has number of turns which have direct contact with the

material melted. (Fig. 1) Coreless induction furnaces have environmentally friendly characteristics. They can be used as holding furnace or casting furnace.

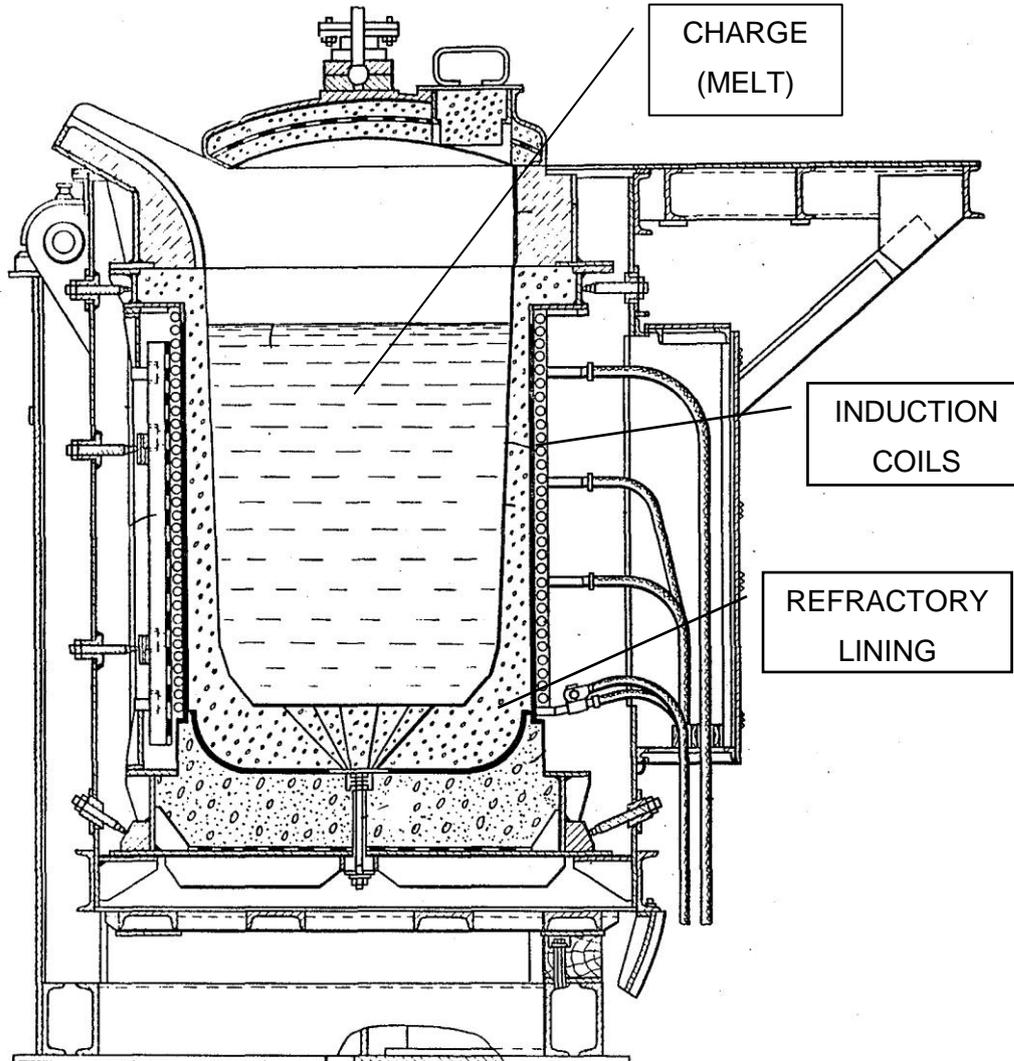


Fig. 1. Induction Melting Furnace [1]

Induced in the metal is a current which heats the latter. Metal is melted under the effect of alternating magnetic field induced by inductor. The power developed in the metal during induction heating depends on many different factors like physical properties of metal, amount of metal, frequency and strength of electromagnetic field etc. A water cooled cylinder protects the inductor from damages while heating. Besides the inside of furnace must be covered by a insulation material called refractory. Refractory lining area stays between melt and induction coils. It is subjected to thermochemical and mechanical effects of molten metal.

1.2 REFRACTORY LINING

Refractory materials retain their strength even at the high temperatures. The oxides of magnesium, calcium, zirconia and silicon carbide are known as refractory lining materials. These materials are classified on the basis of chemical composition as acidic, basic or neutral. Zircon, fireclay and silica are acidic, magnesite is basic, alumina, chromite, carbon, mullite and silicon carbide are neutral. When the refractory lining is made of acidic refractory, it erodes quickly by the chemical interaction of basic slag. If it is acidic lining, it is forming low melting point compounds.

Refractories must have following physical characteristics:

- Retain their strength in high temperatures
- Chemically inert
- Resistant to thermal shock
- Low thermal conductivities
- Coefficients of expansion

Refractory materials could be shaped or unshaped (monolithic refractories). Dry vibration operation is generally used in induction furnace lining. Besides ramming, gunning, spraying, filling, fettling and sand slinging methods are used to install monolithics. Refractory material lifetime depends on dryness of refractory and also compaction ratio. An important cost saving can be made by ramming the refractory mass correctly. It increases amount of charge taken into the furnace. Besides this advantage, refractory ramming process can be done much faster by using designed ramming machine.

Table 1 shows a comparative properties of high density and low density refractories.

Property	High Thermal Mass (High Density Refractories)	Low Thermal Mass (Ceramic Fiber)
Thermal conductivity (w/m K)	1.2	0.3
Specific heat (J/kg K)	1000	1000
Density (kg/m ³)	2300	130

TABLE 1. Typical Refractory Properties (The Carbon Trust, 1993)

Refractory lining is consumable material that is damaged to the conditions of the furnace. When a certain amount of damage occurs, induction furnace operation must be interrupted to repair or replace refractory lining. Replacement of the lining increases furnace downtime.

Refractory material lining requires two steps for induction furnaces:

- Floor portion: Floor material is filled and compacted.
- Wall portion: Liner form is positioned on the bottom refractory. Then liner form creates a wall between former and furnace.

The Right way of refractory installation is essential to higher refractory life. The density of installed material must be observed by controlling the given volume. It depends on space between dry refractory particles. Refractory installation requires skilled labor. An installation could take from an hour to a day or more, depending on the capacity of furnace.

1.3 VIBRATING MACHINE (VIBRATOR)

Vibration of granular materials methods have been used widely in many sectors, especially construction area. Industrial vibrators are in use for two general purpose in construction sector:

Compacting: Mechanical vibrations will cause bulk powdered materials to compact or to consolidate. Increasing compaction and density process will increase strength of material, such as piles or columns in construction sector. Also in this study, a special design vibrating machine will be mentioned which is in use as foundry practice to compact refractory material.

Material Handling: Under the vibration, cohesive powder or bulk material will behave like a fluid. It's commonly used to mount a vibrator on storage bin when it is desired to improve ability to flow.

Vibrator designs vary of depending on the purpose. Two important factors play an important role when designing a vibrator. A vibrator could be classified by frequency and amplitude values. Frequency is the number of occurrences of a repeating event per unit time. [2] f is the frequency in hertz which means number of cycles in seconds. During the case study of thesis frequency counter was used to find out this value. Another

variable is amplitude which concerns effect of impact. Amplitude is the magnitude of change in the oscillating variable with each oscillation within an oscillating system. [3] Depending on these variables, vibrators are classified as frequency vibrator and impact vibrators. When the low amplitude but high frequency is needed especially in smaller furnaces, frequency vibrators are used which have frequency between 2500- 4000 rpm. Impact vibrators are used when low frequency but high amplitude is needed. These vibrators are not suitable for small furnaces and multiple vibrators could be used when necessary.

2 CASE STUDY

2.1 THIRD PARTIES

This project was carried out in accordance with **IDEAL Foundry Technologies** to design a better vibrator which is used to install refractory for coreless type induction furnaces.

Produced machines were sold to several foundries in Turkey and exported to many of foundries and suppliers in the world by these channels.

2.1.1 MAIN COMPANY (IDEAL)

IDEAL was founded in 1981. In the early years, main function and target was pattern production for foundries.



Fig. 2. İDEAL's Company Logo

As a result of successful works and growing demands from customers, it started to provide foundry equipments, machines, establish key-end foundries, give consultancy services, project design, production, installation, education and technical support, along with pattern production.

In 1998, IDEAL started to cooperate with the major companies in foundry sector to meet our customers' demands faster, and present them alternative solutions. It has obtained wide customer portfolio in Turkey, Middle East, East Europe, Africa, Asia and IDEAL became well known, trustworthy brand name. [4]

IDEAL has started to work on vibrating machines for refractory lining since 2006. By this case study concept of ramming machine was clarified and improved totally. Author of this thesis was in technical executive position while the project was on progress.

2.1.2 SECONDARY COMPANY (ALLIED MINERALS)

Allied Mineral Products is the world leader company in the design and manufacture of monolithic refractories and precast refractory shapes. Worldwide, Allied maintains a strong presence with sales to more than 90 countries. These sales are supported by manufacturing facilities in six countries and representatives located in more than 20 countries.



Fig. 3. Allied Mineral's Company Logo

Their product line includes leading edge refractory technology and value added alternatives. That's why IDEAL sees Allied as a good partner to distribute IDEAL Refractory Rammers all over the world. Besides IDEAL, Allied has more partners especially on refractory installation equipment range. These companies are worldwide known brands such as Bosch, Martin Vibrators and Mud Hog.

As after sales and R&D, the project was assisted by Allied Mineral Products. The company has also been working on vibrating systems which are mentioned in following chapters.

2.2 BACKGROUND OF INVENTION

There are several types of vibrators to compact refractory mass. Most of them are operated electrically and having rotary pistons. Rotary electrical vibrators are manufactured by many of companies and have flexibility of mounting to use in different applications such as breakers, large hoppers, settlers, bag fill systems, feeders etc.

2.2.1 ALLIED ELECTRIC VIBRATION SYSTEM (EVS)

Company's previously patented product EVS contains an electric vibrator with mounting brackets and vibration control panel.

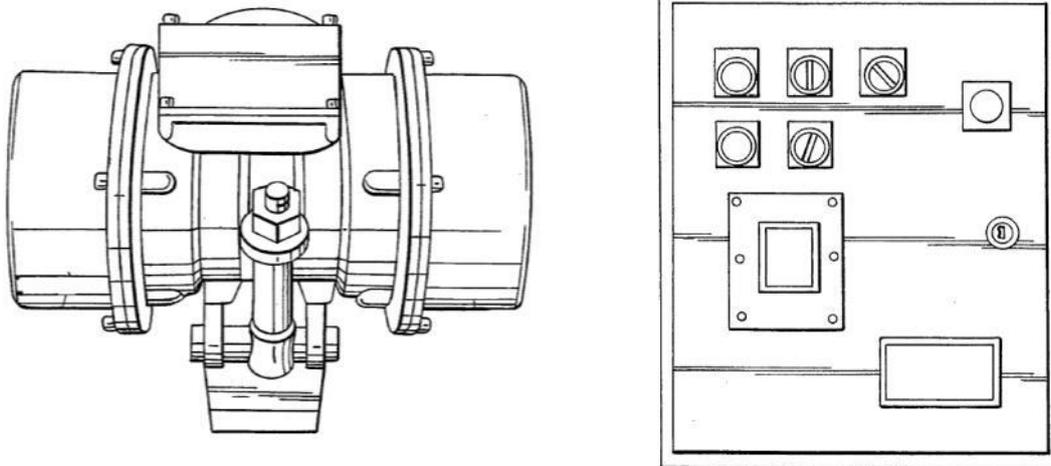


Fig. 4. Allied Electric Vibration System. Electric Vibrator (on the left) and Vibration Control Panel (on the right)

Eccentric weights are located under the motor's side lids. When motor shaft starts to rotate, weight causes centrifugal forces (see Fig. 5). Internal weights of vibrator are designed to be variable based on direction of vibrator shaft rotation enabling the vibrator to operate at various frequencies and amplitudes. [5]

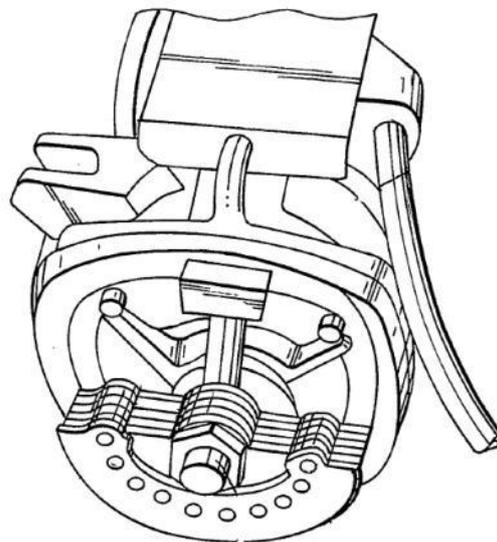


Fig. 5. Allied Electric Vibration Motor

Certainly these centrifugal forces will cause vibration of mounted object. Generally motor is mounted on a plate which is in contact with furnace former. (see Fig. 6)

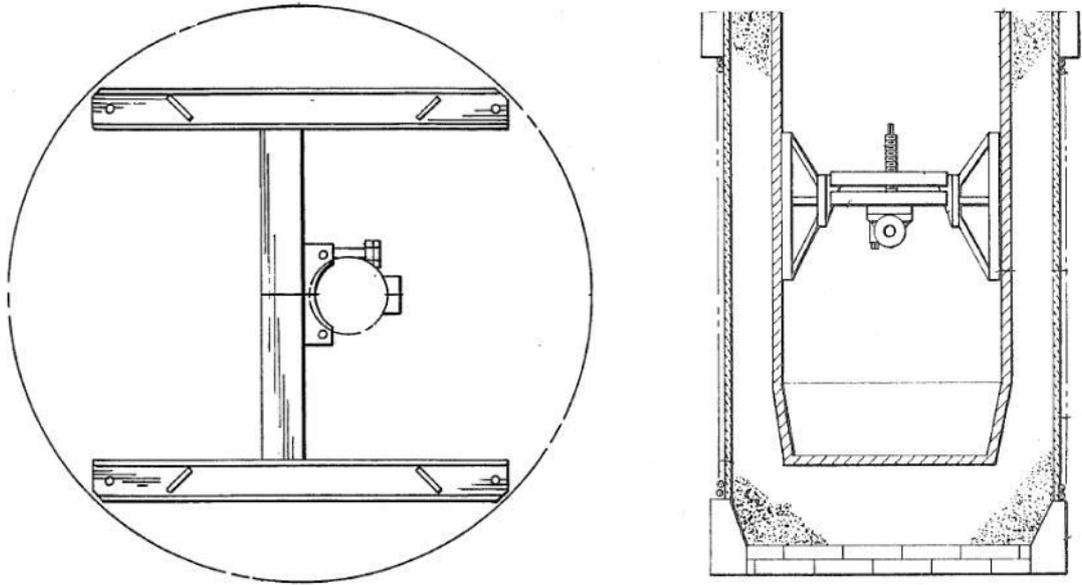


Fig. 6. Allied EVS Application

(Top view on the left, front cross section view on the right)

EVS could be used for different purposes than refractory ramming. It could be used in places where vibration is needed, for example for conveyors, storage bins, feeders, hoppers etc. It is also ideal for inductor lining applications besides coreless induction furnace applications.

2.3 INVENTION

Former refractory ramming methods didn't meet desired requirements such as ease of use and efficiency. Common vibrators need too much labor when mounting. This experienced manpower needed to spend a day for refractory lining in order to achieve desired lining. Besides common vibrators, there are machines such as Allied's Electric Vibrator System (EVS) which could compact refractory material. But most of the time these methods were much more complicated or were not as efficient as manual ramming operation.

Under this thesis project, a new rammer concept was designed from top to toe considering all these needs. All components were chosen carefully on the base of mechanical engineering principles such as mechanics of materials, pneumatic principles, machine design, safety of work confirming to standards. Author of this thesis had a chance to follow manufactured product also in sales progress. At the moment, designed refractory ramming systems are in use in several of companies worldwide.

2.3.1 GENERAL OVERVIEW

Fig. 7 shows all components in designed system. A complete refractory ramming system contains;

- 1) Operating Panel (Optional)
- 2) Crane Support
- 3) Crane Motor
- 4) Wall Ramming Machine (Main Unit)

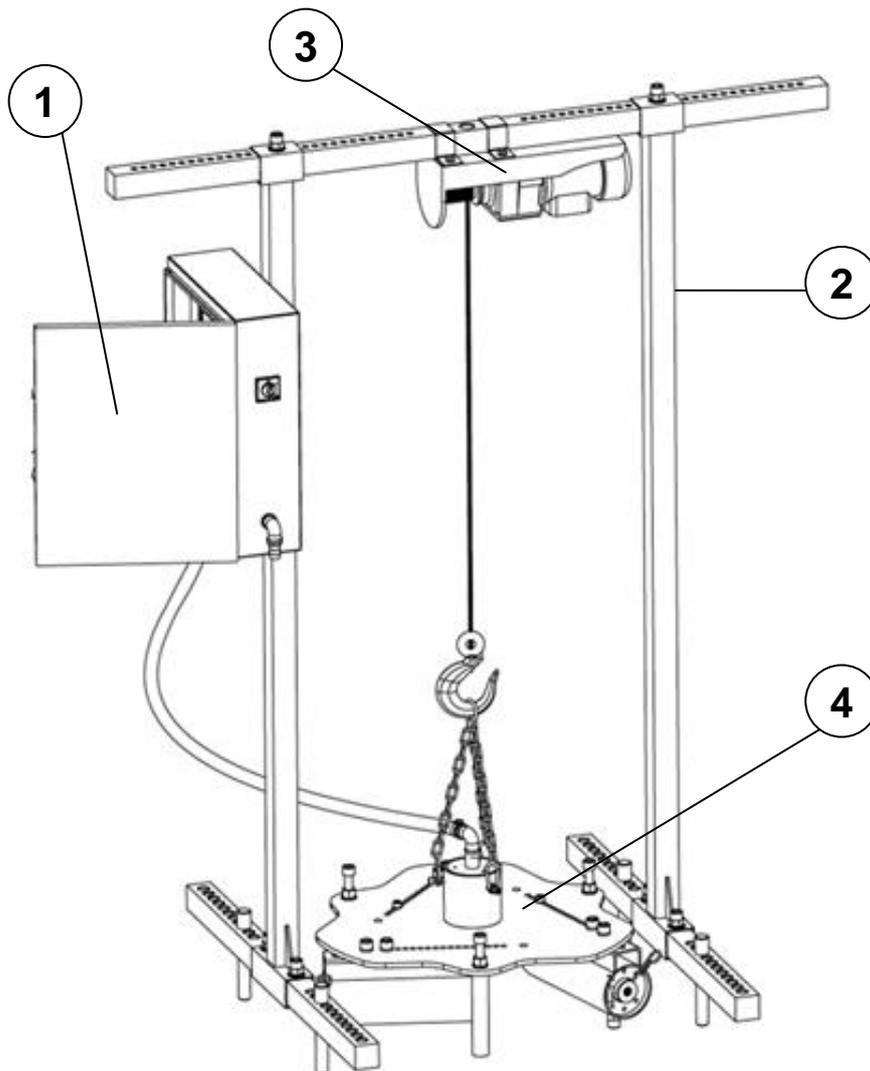


Fig. 7. Complete Refractory Ramming System Design

Ramming machine (vibrator) (4) is hanged on a crane (3) on the top of induction furnace, operated by panel (1). Crane (3) pulls ramming machine (4) up/down while operating. 5 bar air input is necessary to run ramming machine's pistons and 220 V AC electric current is needed to run operator panel.

2.3.1.1 Wall Ramming Machine

Wall ramming machine (see Fig. 8) is the equipment to compact induction furnace's side sections. It has linear pistons (4.2) inside their slots mounted horizontally on a chassis frame (4.1). Air distribution and rotation is provided by rotation unit (4.3).

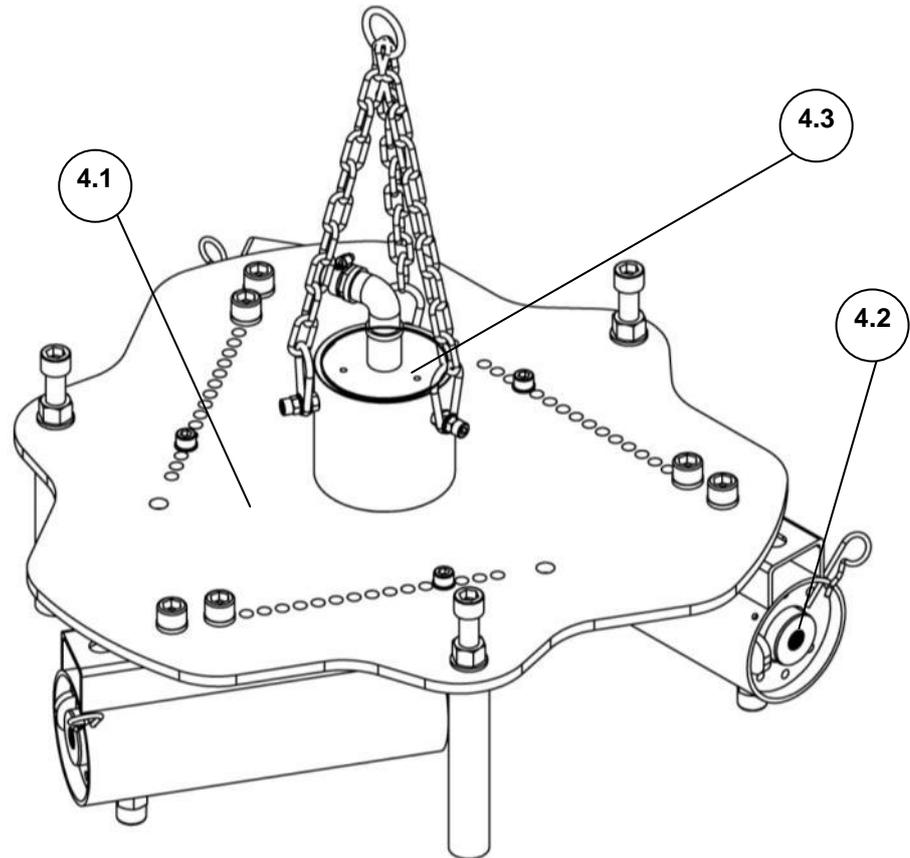


Fig. 8. Standart (Three Arm) Wall Ramming Machine

2.3.1.2 Bottom Ramming Machine

Bottom ramming machine (see Fig. 9) is the equipment to compact bottom part of induction furnace lining. Only one linear piston (5.1) is located in the middle of a steel flange (5.2) perpendicularly. Main body is reinforced by support rings and tie pieces. Machine is hung by the handling rings on the crane to position.

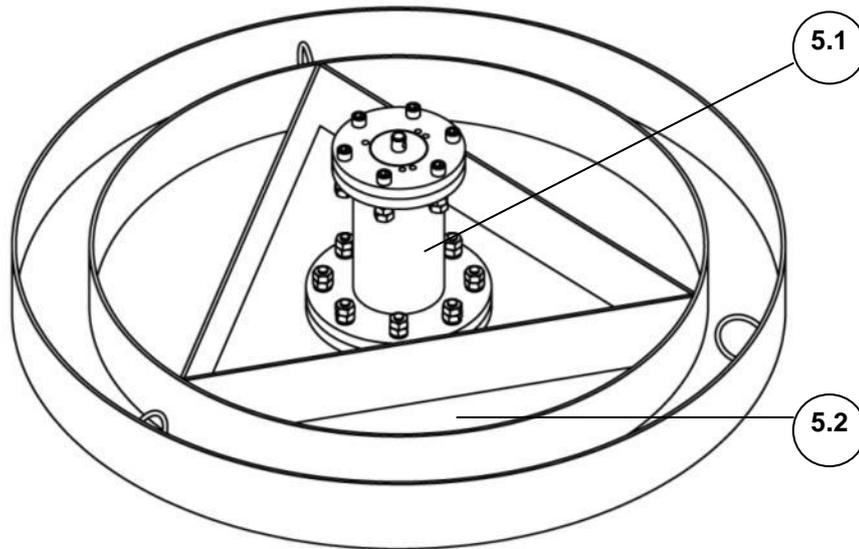


Fig. 9. Standart Bottom Ramming Machine

2.3.2 OPERATION

Refractory ramming operation has following steps:

- Bottom ramming operation
- Wall ramming operation

Operation starts with bottom ramming. Needed amount of refractory material is filled inside the furnace on the bottom. Initially this refractory material is to be compacted by using bottom ramming machine (see Fig. 8). Bottom ramming machine has a linear piston (vibrator) which works vertically and vibrates its flange (body). This vibration compacts granular refractory material.

Just after bottom ramming is completed, bottom rammer will be taken out and former will be placed to create a space between furnace and former. This space will be filled with refractory material. When refractory material is filled, wall ramming machine will be hanged on the crane (see Fig. 9). After placing the wall rammer close to the bottom of furnace, wall ramming operation will be started. Wall rammer has 2,3 or 5 pistons mounted on one chassis frame. The amount of piston is chosen depending on furnace capacity. When more frequency is needed, more pistons will be added. Wall rammer pistons strike former's wall physically. This force will create an amplitude and frequency. Wall ramming starts at the bottom and ends on the top of former. This means ramming is done in all levels of former equally. This is the main advantage of refractory ramming machine.

Since preparation is crucial for lifetime of lining material, vibrating machine is substantial for foundries using induction furnaces. With machined lining operation:

- Refractory material is compacted with equal density which extends life of refractory
- Cracks and gas pockets risks are minimized
- Less manpower is used
- Lining is made much more faster

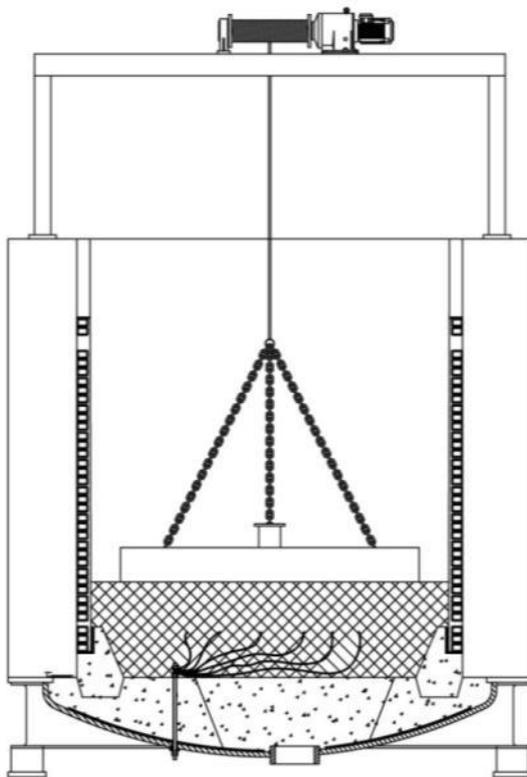


Fig. 10. Bottom Ramming Operation
(on the left)

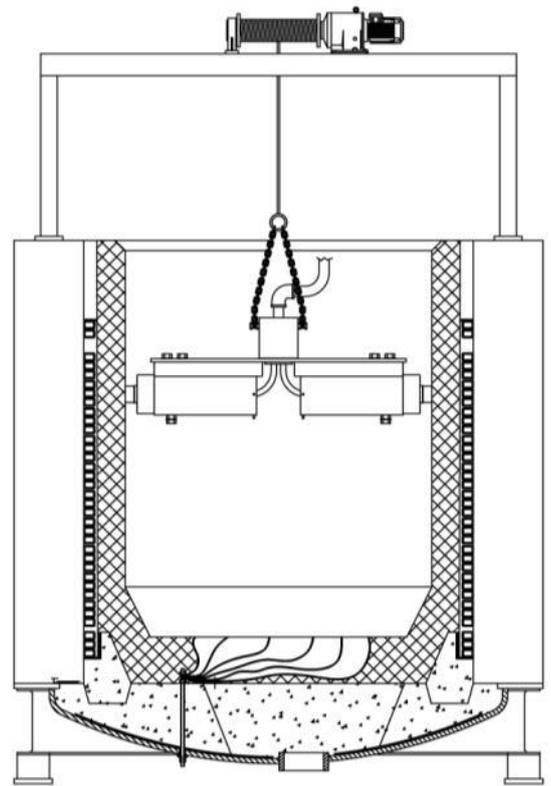


Fig. 11. Wall Ramming Operation
(on the right)

2.3.3 PISTON DESIGN

Piston is the most crucial component of ramming machine. It's commonly called vibrator and vary different types according to area of usage. "Piston sleeve" (see Fig. 12) have a role of bedding to "Piston pin" (see Fig. 13). It's very important to work with small tolerances between these two touching surfaces of pin and sleeve.

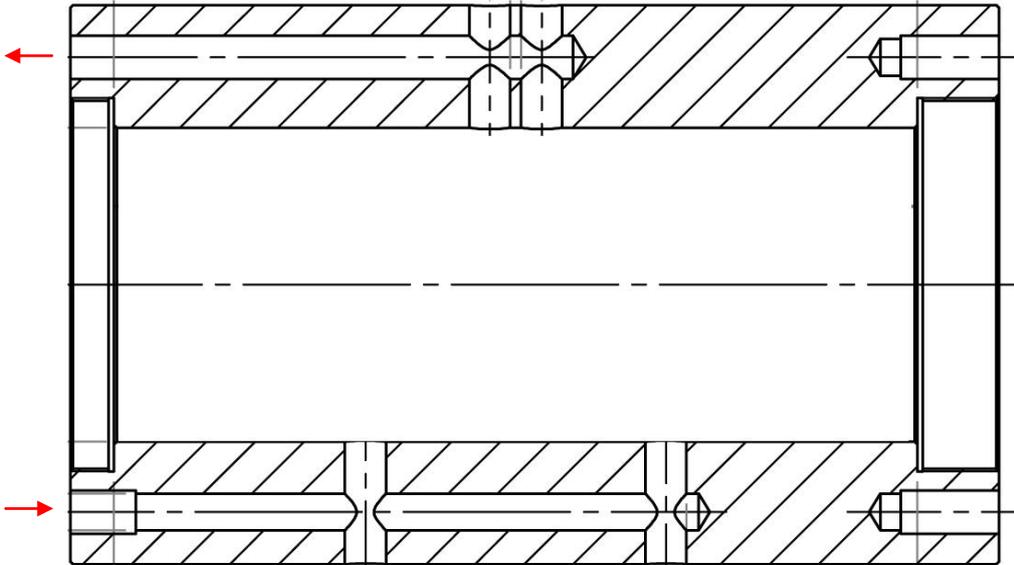


Fig. 12. Piston Sleeve (Slot)

Piston sleeve (slot) has air inlet and outlet to distribute air flow. These air channels bring a new feature to vibrator which will be mentioned in “2.3.3.1 Theory” section. Besides the air channels there are two lids from both sides which close the system. Under the lids there are sealings for better air insulation.

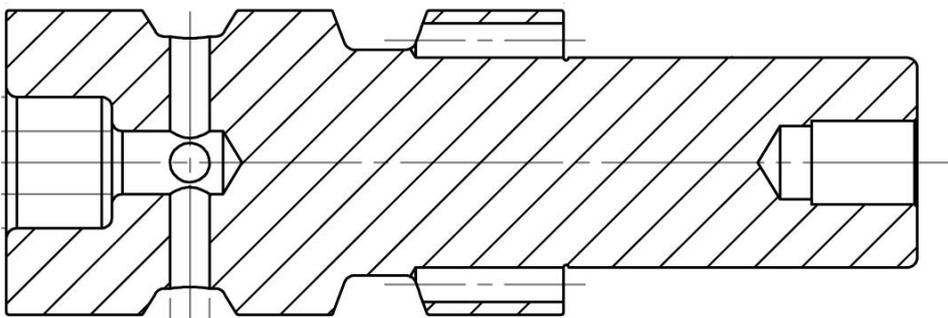


Fig. 13. Piston Pin (Rod)

Piston pin (rod) is “moving part” in vibrator. It’s mounted into the sleeve and moves forward and backward by the pressured air. On the rear side of rod, there are air distribution channels horizontally and vertically. Front side hits to the former while the operation.

2.3.3.1 THEORY

In this vibrator design, there is no such a components like positioning spring etc. Piston is manufactured as single acting cylinder but because of air distribution design it

behaves like double acting cylinder. Design allows opening and closing air channels regarding to its positions automatically where will lead a rapid forward-backward movement of piston pin. To reach this aim, following dimension scale must be achieved:

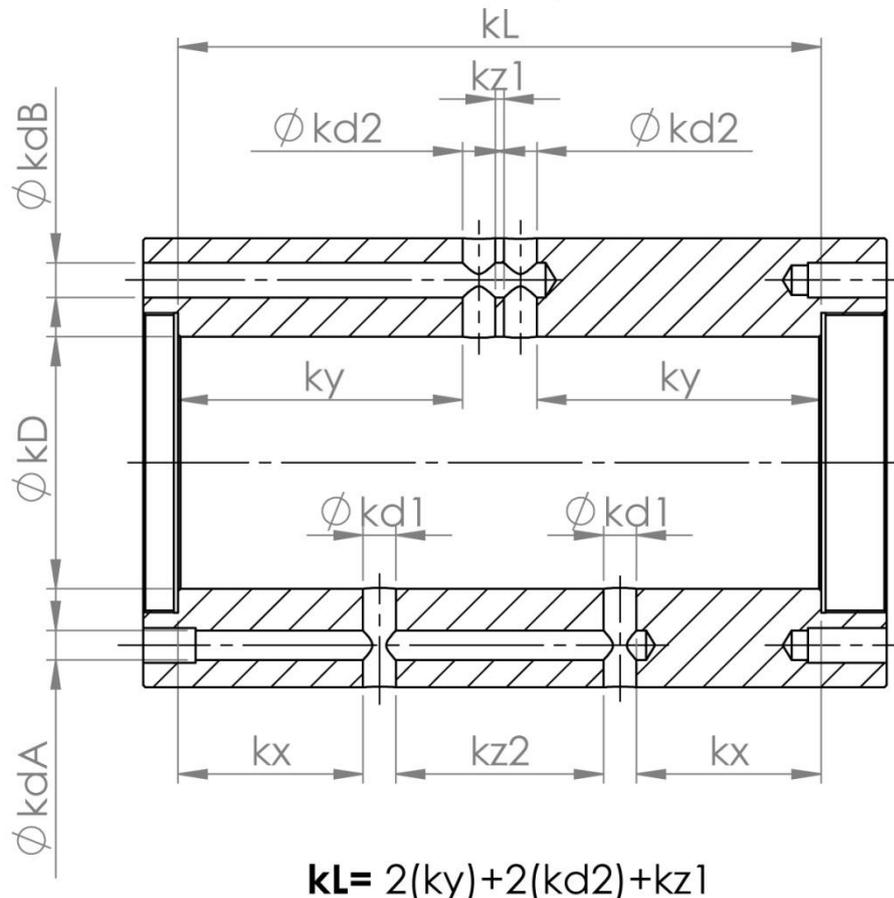


Fig. 14. Proportional Scaling of Piston Sleeve (Slot)

Fig. 14 explains the proportional scaling of piston sleeve. This **symmetrical** scaling could be modified to any dimension. Abbreviations are described as it follows:

kL = Length of piston pin, kD = Diameter of piston pin

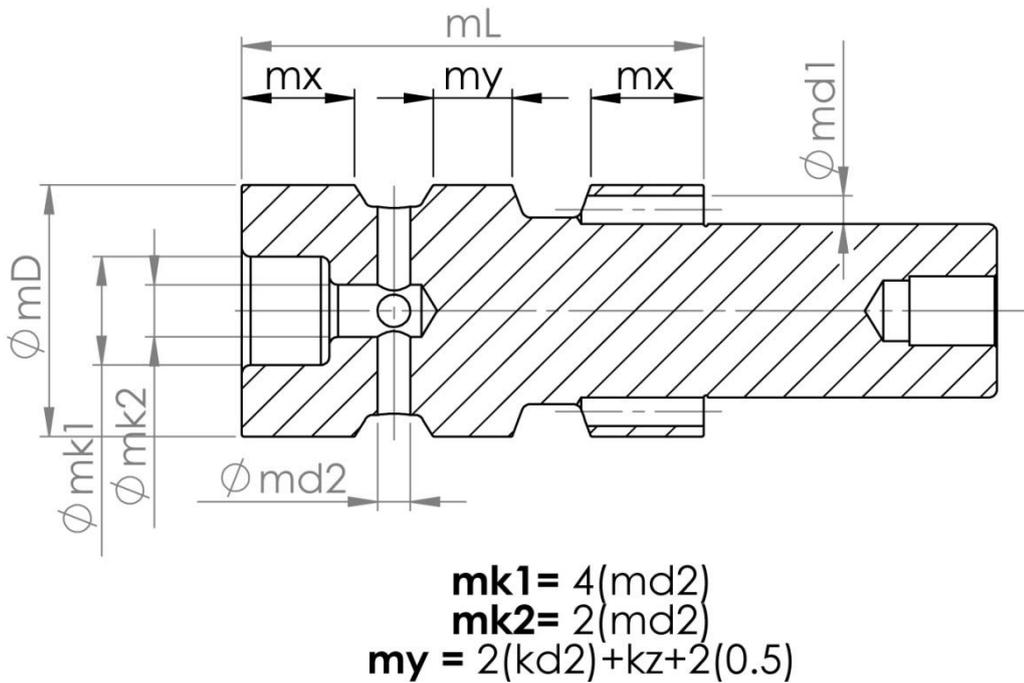


Fig. 15. Proportional Scaling of Piston Pin (Rod)

Fig. 15 explains the proportional scaling of piston pin. This scaling could be modified to any dimension as long as same numbers are applied to piston sleeve. Abbreviations are described as it follows:

mL= Length of piston sleeve, **mD**= Diameter of piston sleeve

“my” describes piston stroke and defined by two times piston intake holes (kd2) + half way of slot stroke (ky) + two times headroom (0.5).

Summarizes piston stroke could be defined as; kL – mL.

Theory of vibration operation has three steps which could be named by the position of piston rod:

- Full stroke position (see Fig. 16)
- Zero position (see Fig. 17)
- Balance position (see Fig. 18)

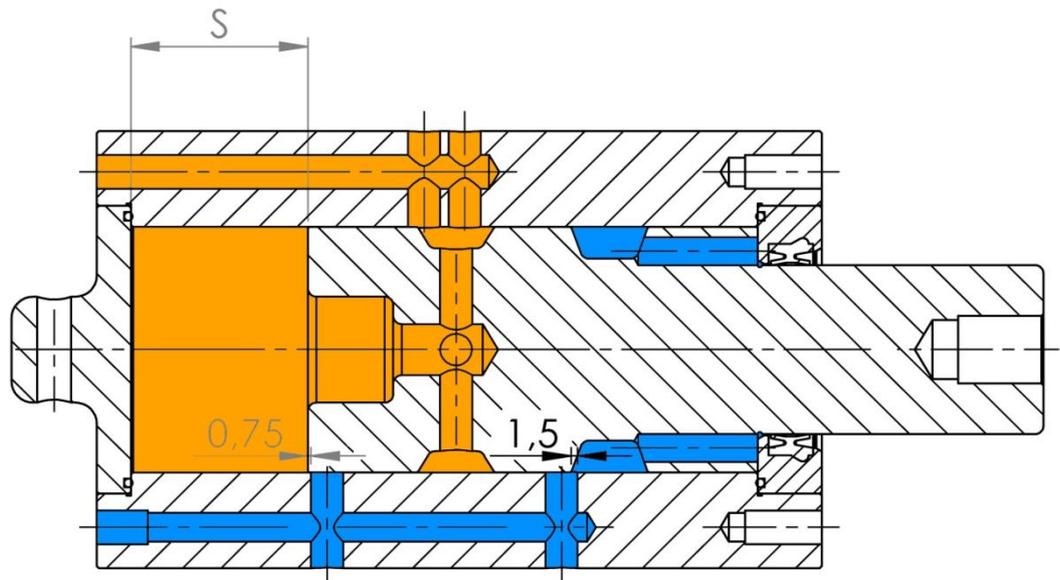


Fig. 16. Full Stroke Position

Full stroke (see Fig. 16) is the position where piston pin is fully outside of sleeve. This is the maximum stroke out position. In this position air inlet pressure (shown as blue) exudes from the channels and reaches to front of piston. After pressure increase in this section, piston pin is forced to move backwards (inside the piston sleeve). Meanwhile in the back side of piston, air is exhausted until the time exhaust holes are blocked by piston pin which is shown in Fig. 18.

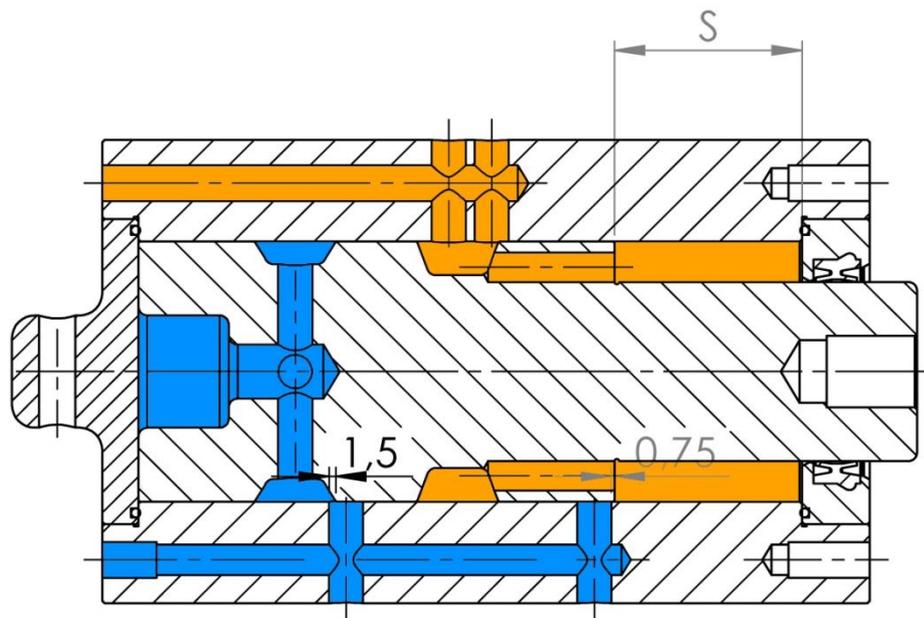


Fig. 17. Zero Position

Zero position (see Fig. 17) is the moment when piston pin is fully inside the sleeve. This is called minimum stroke out position or stroke in position too. Pressured air leaks

through the blue marked channels to the back side of piston. When pressure increased piston pin is forced to move forward. Meanwhile in the front side of piston, air is exhausted until the time exhaust holes are blocked by piston pin which is shown in Fig. 18.

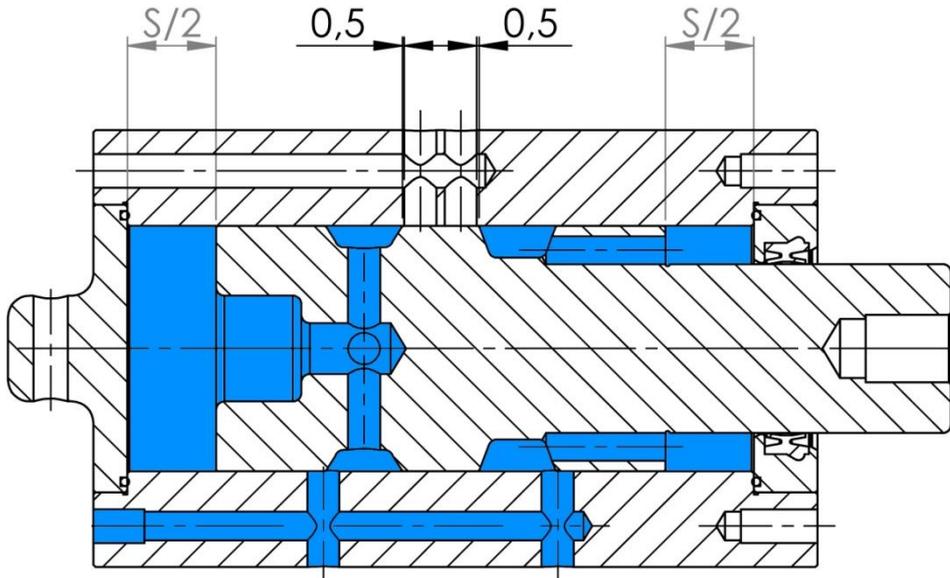


Fig. 18. Balance Position

Balance position exists only in theory. Practically it's quite much impossible to take the piston pin into this position. Theoretically piston is balanced. Neither has it moved forward or backwards because of pressured air forces from both side of pin.

When piston is running piston pin should never hammer piston sleeve's wall. An air pillow appears by compressed air on the opposite side of piston in each direction of movement. But when the air inlet pressure is over than maximum value (which is 6 bar) piston pin could start to hit inside wall of piston sleeve. This will lead material deformation. That's why must be avoided.

2.3.3.2 MATERIAL SELECTION

Most of the vibrator piston bodies are made by aluminum material. But because of foundry working conditions more long-lasting material must be chosen to maximize the lifetime of machine. Following materials are chosen for piston components:

Piston Sleeve (Slot) Material:

Class:	4140 (Alloy Steel)
Alloy Composition:	Carbon: 0,38- 0,43
	Chromium: 0,8 – 1,1

Manganese: 0,75 - 1

Molybdenum: 0,15 – 0,25

Features: Chromium, molybdenum, manganese, low alloy steel noted for toughness good torsional strength and good fatigue strength.

Applications: Pistons, gears, etc.

Machinability: Machinability of this alloy is good. [6]

Piston Pin (Rod) Material:

Class: 8620 (Alloy Steel)

Alloy Composition: *Carbon:* 0,18- 0,23

Chromium: 0,4 – 0,6

Manganese: 0,7 – 0,9

Molybdenum: 0,15 – 0,25

Nickel: 0,4 – 0,7

Features: AISI 8620 is a hardenable chromium, molybdenum, nickel low carbon alloy steel often used for carburizing to develop a case hardened part. This case hardening will result in good wear characteristics.

Applications: Gears, ring gears, shafts and crankshafts. (carburized)

Machinability: Machining is done prior to carburizing to within as close tolerance as possible. After carburizing only grinding is possible. [6]

2.3.3.3 MANUFACTURING PROCESS

CNC processing machine (4 axis lathe) is used as first step of manufacturing process. After this step case hardening is done to AISI 4140 until 40-43 HRC. For the piston pin, AISI 8620 must be case hardened until 55 HRC. It's very important that complete piece hardening cause ductility in inner structure of material. Instead it must be case hardening by nitration only for surface of material. This will avoid deformation by friction while the operation. After case hardening last step must be grinding to bring dimensions into the tolerance. For the piston pin; surface grinding machine, and for the sleeve; hole grinding machine is used. This last step is very crucial, so the tolerance between touching surfaces of pin and sleeve is approximately %5. When piston pin diameter is greater or the sleeve inside diameter is smaller than desired value, piston could be stuck while operation.

2.3.4 MANUAL/AUTOMATIC CRANE

Crane system is an optional product to make ramming fully automated or semi-automated. It has a lifting crane mounted on hanger, and a PLC operated control panel (only in automatic crane) to automate complete ramming process. It is suitable for different size of furnaces. It is easy to mount and demount. It is necessary to use automation especially for bigger size of furnaces when refractory ramming operation takes too long time. It will minimize the risks caused by human and complete lining fast and efficient.

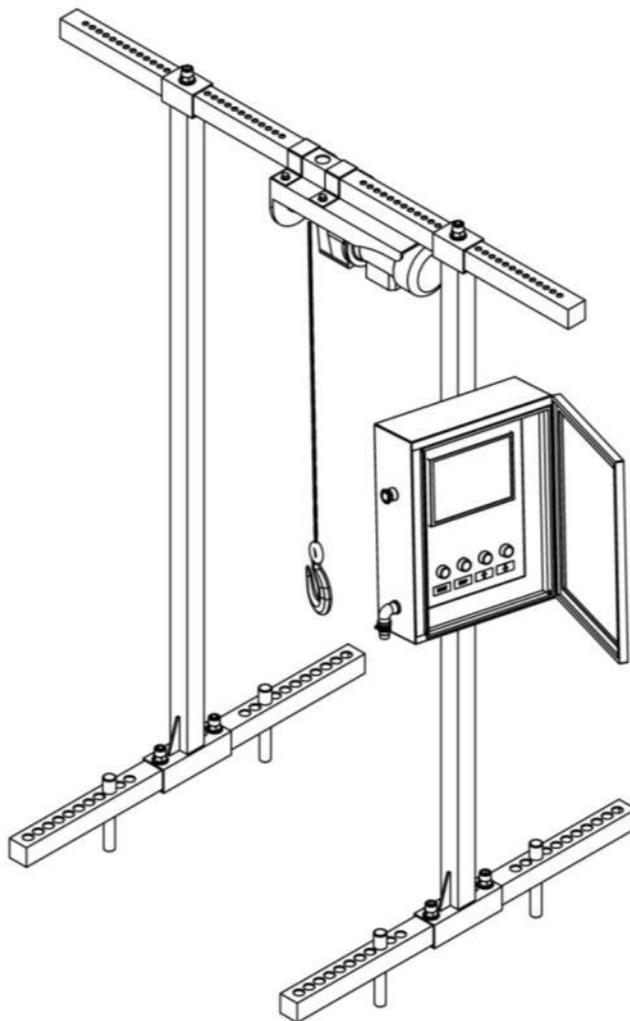


Fig. 12. Automatic Crane System

2.3.4.1 PLC

PLC control is a part of automatic crane system. Besides the crane, control is made on operator panel. Operator panel consists start, stop, up, down buttons and a touch screen. PLC programming makes ramming fully automated. By this new design, it is also possible to know refractory material needed for wall part and bottom part separately. It was designed as Turkish and English languages during this project.



Fig. 9. PLC Operation - Main Menu

Main menu directs operator to desired action. Refractory calculation, bottom ramming and wall ramming modules are available at first prototype. There is also memory function to save and recall from the memory.

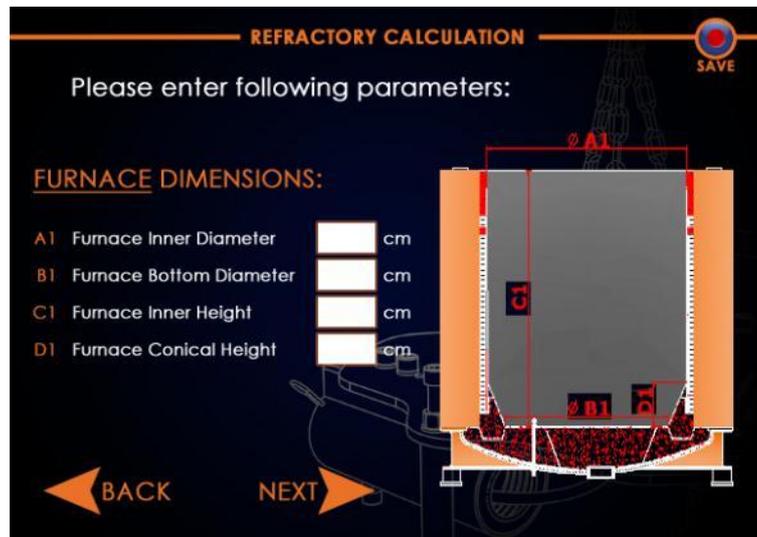


Fig. 9. PLC Operation – Refractory Calculation

In order to project refractory material needed, volume of furnace must be calculated. Following parameters must be entered by operator:

A1: Furnace Inner Diameter

B1: Furnace Bottom Diameter

C1: Furnace Inner Height

D1: Furnace Conical Height

To calculate furnace's volume:

Cylinder:

$$\pi \times \left(\frac{A1}{2}\right)^2 \times (C1 \times D1) = V1_{cylinder}$$

Frustum of cone:

$$\frac{1}{3} \times \pi \times D1 \left[\left(\frac{B1}{2}\right)^2 + B1 \times A1 + \left(\frac{A1}{2}\right)^2 \right] = V2_{frustum\ of\ cone}$$

Total volume:

$$V1_{cylinder} + V2_{frustum\ of\ cone} = V_{furnace}$$

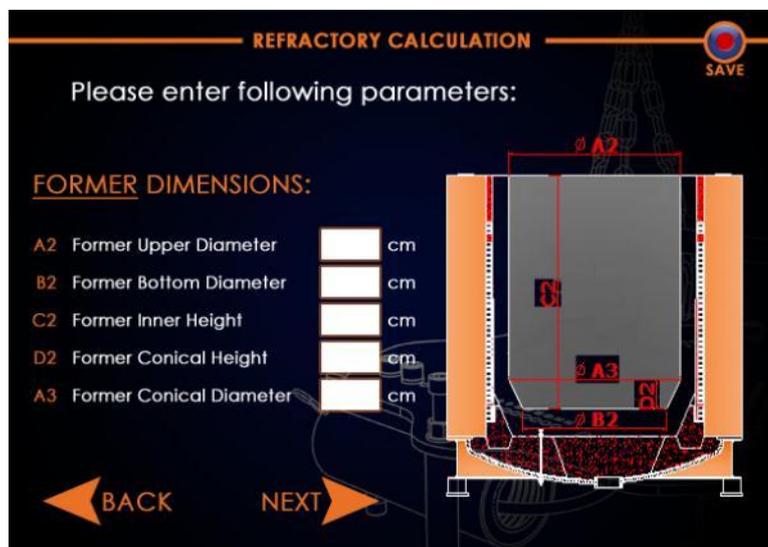


Fig. 9. PLC Operation – Refractory Calculation

After finding out furnace volume, former's volume must be calculated. Following parameters must be entered by operator:

A2: Former Upper Diameter

B2: Former Bottom Diameter

C2: Former Inner Height

D2: Former Conical Height

A3: Former Conical Diameter

To calculate former's volume:

Upper frustum or cylinder:

$$\frac{1}{3} \times \pi \times (C2 - D2) \left[\left(\frac{A2}{2} \right)^2 + A2 \times A3 + \left(\frac{A3}{2} \right)^2 \right] = V3_{upper\ frustum}$$

Lower frustum of cone:

$$\frac{1}{3} \times \pi \times D2 \left[\left(\frac{A3}{2} \right)^2 + A3 \times B2 + \left(\frac{B2}{2} \right)^2 \right] = V3_{lower\ frustum\ of\ cone}$$

Total volume:

$$V2 + V3_{lower\ frustum\ of\ cone} = V_{former}$$

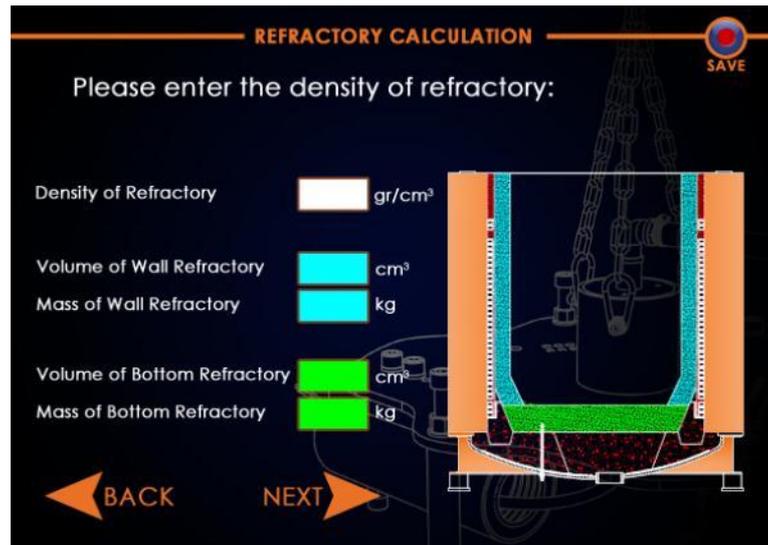


Fig. 9. PLC Operation – Refractory Calculation

When furnace and former's volume's are known, PLC needs density of refractory material in order to monitor mass of refractory needed. Refractory material must be viewed seperately as for the bottom part and wall part.

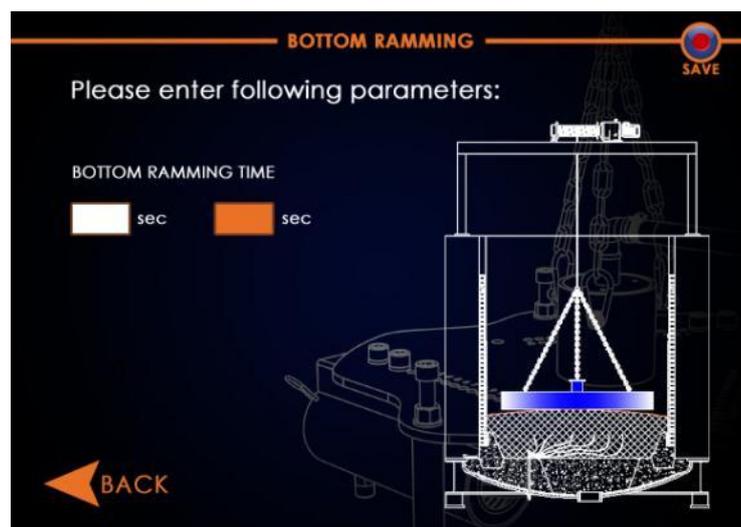


Fig. 9. PLC Operation – Refractory Calculation

As long as needed material is placed on furnace bottom, bottom ramming operation could be started. The operator enters desired time and presses start button on panel. Thereby air valve is opened and ramming operation starts.

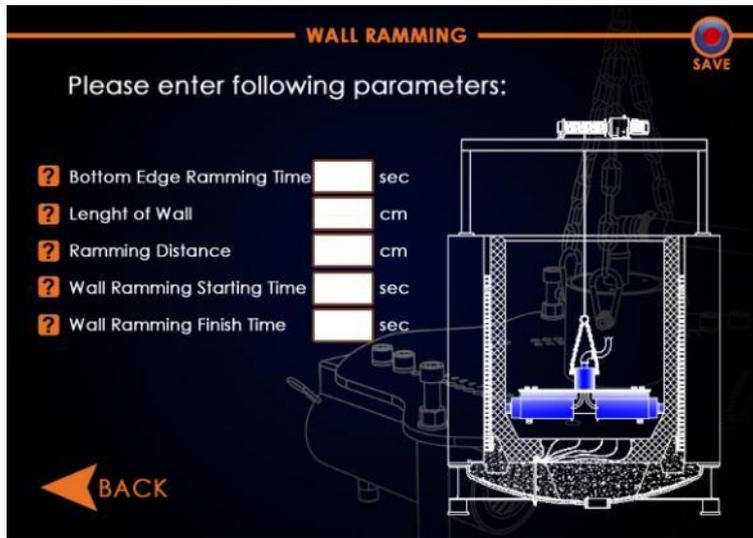


Fig. 9. PLC Operation – Refractory Calculation

3 CONCLUSION

After this successful thesis work, new refractory ramming systems were taken under patent protection and the machines have been sold to many of companies worldwide. IDEAL Refractory Ramming Systems improves refractory material lifetime by %20 more. This brings a good financial profit to the customer. Besides financial advantage, customer could define new refractory installation date easier, as long as he/she could predict lifetime of refractory with identical ramming operation each time.

The author of thesis has used engineering basics knowledge in design, cost, and management, manufacturing processes etc. points. Furthermore, he has earned a huge experience by carrying out this project from top to toe.

The next R&D steps could be focused on automated systems and examination of compacted materials under certain vibration frequency. After these important issues clarified, the vibrator pistons used in ramming machines could be also used for material handling processes. It's surely beyond doubt that vibrating systems has a big area of usage in industry.

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