Innovative Inductive Cold Crucible Configurations with improved Efficiency

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Abstract: The inductive cold crucible is a very interesting tool for processing materials by magnetic field without pollution. It is more and more used in various areas like in aeronautic, photovoltaic, waste recycling industries and also for medical applications. As the cold crucible in its current state of art has a low energetic efficiency, the better comprehension of this process thanks to recently improved multiphysic modeling tools and experimental measurements gives some guidelines for experimenting new kinds of cold crucibles. These elements are presented in this paper, especially the numerical modeling and first tests operated on a 'thin shaped cold crucible' which seems very promising concerning the efficiency improvement and also a better overheating of liquid charge.

Key words: inductive cold crucible; levitation melting; skull melting

1 Introduction

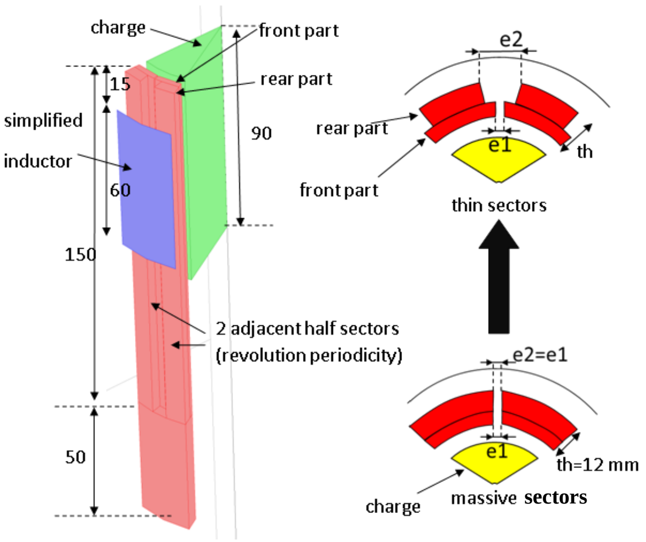
The inductive cold crucible is more and more used for processing of high degree purity materials in various applications ranging from investment casting for aeronautic, automotive or medical parts (titanium alloys) [1,2], photovoltaic silicon purification and crystallization[3], to waste recycling installations (like nuclear waste vitrification processes). The major drawback of the current cold crucible configurations whose sectors are massive shaped is the low energetic efficiency making them high power consuming and low overheating[1]. There are two main families of cold crucibles: the levitation melting cold crucible (LM) which has an inner pocket shape and which is devoted to investment casting applications, and the bottom opened straight cold crucible (4C) devoted to continuous casting (4C, meaning "Continuous Casting Cold Crucible") [3] .

Former results based on experimental and numeric modeling approach on a current cold crucible configuration with a massive shape of copper sectors [4] gave the guide lines for a new "thin shaped cold crucible" which is based on the set up of copper sectors each made of a thin sheet with external water cooling.

Thus such a new "thin shaped cold crucible" has been figured out and the first characterization results are presented in this paper. Numeric modeling (part 2) gives some guidelines of the design and shape optimization of this thin-4C cold crucible. Then part 3 shows the main results of comparative tests operated both on a classical massive-4C cold crucible and on an innovative thin-4C cold crucible. These tests are performed thanks to calorimetric power balance measurements in the inductor, cold crucible and a "cold" (water cooled) metallic stainless steel solid charge. These tests show clearly a much better efficiency of the new suggested thin-4C crucible than the classical massive-4C one. At last in part 4 some recent multiphysic numerical comparative results between the classical massive-LM crucible and the new suggested thin-LM crucible are given, showing a better stability of the levitated liquid charge, which is promising for this thin-LM extension, especially for levitation melting applications where the overheating is important.

2 Design elements of the new suggested "thin-4C" continuous casting cold crucible

The former analysis [4] of the classical massive-LM crucible showed that in each copper sector the slits vertical adjacent surfaces consume the major part of the Joule losses in each such sector. Thus the idea is to decrease these slits surfaces and also to increase the distance between them in the new thin-4C suggested crucible. For that, with the Comsol finite element solver, a parametric sweep is operated on a 3D electromagnetic numeric



(a) (b)

Fig. 1- Numeric model (a) and parametric sweep (b)

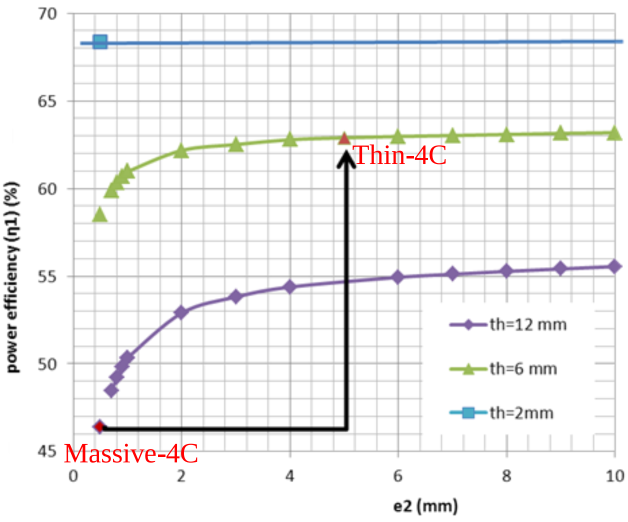


Fig. 2 Charge coupling efficiency with respect to e2 for different radial thicknesses th

model for passing from the initial massive cross section (curved rectangle) to the thin shape as showed in **Fig. 1(b)**, by varying both the radial thickness "th" and also the distance "e2" between the rear parts (which is the water cooled part of the thin-4C crucible) of two adjacent sectors. The gap "e1" between the front parts which are the "sheets" building the thin part of the sectors of the thin-4C crucible (radial thickness 2 mm) remains constant and equal to e1=0.5 mm. Thanks to the revolution periodicity of the whole 12 sectors crucible (inner diameter: 70 mm), the model includes only a set of two half sectors which are electrically connected together in the bottom part and the main dimensions are given in **Fig. 1(a)**. The inductor is simplified and simulated by a current density layer (Ø= 100 mm/height: 60 mm) equivalent to a real four turns inductor with a 750 A (rms) current (frequency: f= 60 kHz). The charge (ρ=100 μΩ.cm) set inside the crucible is cylindrical (Ø=64mm/height: 90 mm). The two parameters e2 and th are swept (e2 increases / th decreases) from their initial value (e2=e1=0.5 mm / th=12 mm) corresponding to the initial massive-4C crucible in order to give the tendencies for finding optimal values for the new thin-4C crucible. These parameters must also be taken into account for the technological aspects for the manufacturing. The main results of this parameter sweeping are given in **Fig. 2**. This Figure shows the coupling efficiency (η1) of the charge (ratio of power induced in the charge over total power sectors+charge / simplified inductor not included) with respect to e2 and for different radial thicknesses th. These results show clearly that the efficiency tends to a constant limit for e2 greater than 3 to 5 mm. This limit is function of radial thickness and the best efficiency (68%) is obtained for a minimum th value of 2 mm. This configuration could be obtained if, as it is intended in a second step, the rear cooling part is manufactured in an isolating material like ceramic which could then be welded to the copper sheet-like front part (in the current first validation step the rear cooling part is in copper). Thanks to this study a new experimental device has been designed (thin-4C, th=6mm, e2=5mm, e1=0.5mm) and manufactured, with the same inner dimensions as an already existing (Massive-4C, th=12mm, e2=e1=0.5mm), in order to compare the two configurations (**Fig. 1**). An improved efficiency from 47% to 63% is expected.

3 Experimental comparison between the massive-4C and the thin-4C cold crucible

In this section the main results of an experimental comparison between the reference massive-4C crucible (th=12mm, e2=e1=0.5mm, **Fig. 1(b)** bottom) and the new thin-4C crucible design (th=6mm, e2=5mm, e1=0.5mm) defined by the former parametric sweep are presented. **Fig. 3** shows the two crucibles. The rear part of the thin -4C crucible includes the two up and down water cooling channels and is welded on the front sheet part. These 12 sectors water cooled crucibles are set in an induction heating installation fed by a 50 kW solid state converter (working frequency 60 to 65 kHz). A cylindrical water cooled stainless steel solid charge (Ø=64 mm/height: 90mm) is set inside the crucibles as showed in **Fig. 4**. A four turns inductor (inner Ø=90 mm/height: 60mm) surrounds the crucibles and builds a parallel oscillating circuit with a capacitor bank. The generator is operated at a given power of P= 25 kW. The power repartition is measured by calorimetric balance in all the sub-assemblies of the melting unit (capacitor bank, inductor, cold crucible and solid charge) which are all fitted out with water flow rate and temperature sensors.

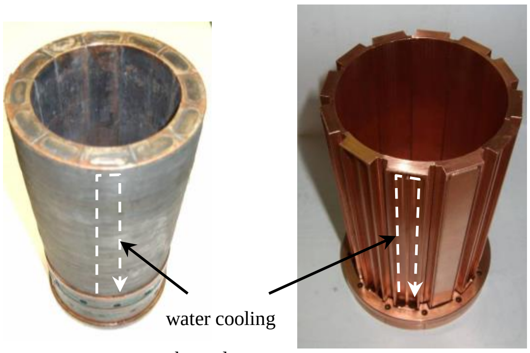


Fig. 3 (a) Massive-4C crucible and (b) Thin-4C crucible

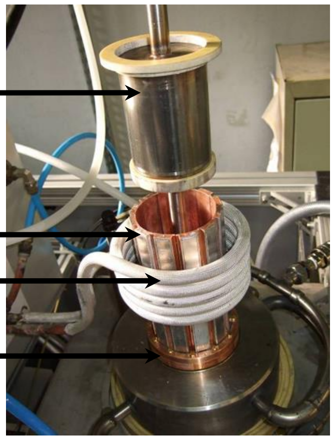


Fig. 4 Experimental device for power efficiency measurements

The results given in **Table 1** show the measured power consumption (in kW and % of total power) for the two crucibles.

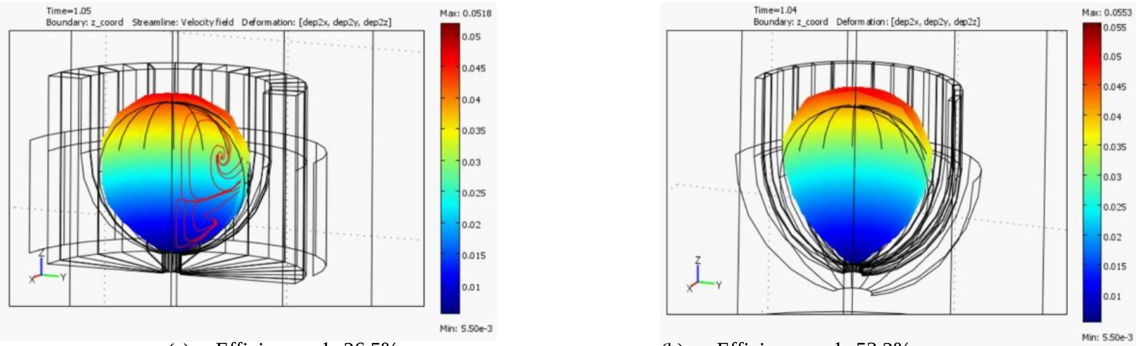
Table 1 Power repartition (kW and % of total) for massive-4C and thin-4C crucible tests (generator power 25 kW)

Sub-assembly	Capacity box	Inductor	Cold crucible	Charge	Total	Efficiency η1 (%)
Massive-4C (kW)	0.4	5.1	8.2	7.5	21.1	-
Thin-4C (kW)	0.5	5.7	5.8	12.8	24.4	-
Massive-4C (%)	1.9	24.0	38.6	**35.5**	100	**47.9**
Thin-4C (%)	2.1	23.0	23.4	**51.4**	100	**68.7**

The results give a global efficiency going from 36% for the massive-4C crucible up to 51% for the thin-4C crucible, meaning an efficiency relative increase of almost 45%. This shows clearly the energy consumption saving obtained with this thin crucible technology, meaning that the total power can be reduced with the same injected power in the charge. In comparison with the model description, the ratio (η1) ratio of power induced in the charge over total power (cold crucible + charge) gives the same tendency for the Massive-4C crucible (48%) and also the Thin-4C crucible (68%) which is a little bit higher. This interesting efficiency improvement has also been validated by real heating and melting experiments with titanium alloy.

4 Extension to the thin-LM levitation melting crucible configuration

An extension of the former presented thin-4C crucible to the thin-LM levitation melting crucible is currently under development. The expected efficiency improvement should be even better than for the 4C configuration. **Fig. 5** shows the final steady state shape of a levitated liquid titanium charge calculated with a 3D multiphysic coupled numeric model set up with the Comsol finite element solver already described in a former publication[5] for both a massive-LM **Fig. 5(a**) and a thin-LM **Fig. 5(b**) crucible of same inner shape and with the same number of inductor Ampere-turns. Obviously the thin-LM crucible gives a better levitated charge with half the total power of the massive-LM one and a twice better efficiency, which seems very promising for the thin-LM crucible able to levitate a 10kg titanium charge whose design and tests are forecast. In a first step the rear cooling part is in copper and in a second step this rear part will be made of an isolating ceramic material, which should give an even increased efficiency.



(a) Efficiency η1=26.5% (b) Efficiency - η1=53.2%

Fig. 5 Numerically calculated steady state shape of a liquid titanium charge for (a) massive and (b) thin-LM crucible

5 Conclusions

In this paper some main results of an optimizing work for more efficient cold crucibles are presented. Thanks to recent 3D multiphysic numeric models the phenomena involved in the cold crucible processes are now better understood. This is very useful for designing new thin cold crucibles with a much better efficiency. Especially the important efficiency and levitation quality improvements expected for the thin-LM levitation melting cold crucible configuration will be a key point for the extension of the industrial applications, since the corresponding installations will consume less energy and it will be also probably possible to much better overheat the more stable levitated liquid which is a fundamental requirement of some industrial processes.

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