PROMOTING INDUCTION HEATING – STEAM GENERATORS FOR MEDICAL STERILISATION: INVESTIGATION OF ENERGY-EFFICIENT DESIGN GUIDELINES

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ARTICLE INFO

***Article history*:**
Received: 27.01.2021.
Received in revised form: 01.04.2021.
Accepted: 06.04.2021.

Keywords:
Energy Efficiency
Induction Heating
Steam Generator
Medical Sterilisation

DOI: https://doi.org/10.30765/er.1790

Abstract:

Saturated steam sterilisers are one of the most energy consumers in hospitals. Induction heating (IH) could be one of the energy saving solutions considering its proven potential in industrial applications such as steam generation (SG) and pasteurisation. Hitherto, there are no studies in literature about this field except one for dentistry. In this review paper, we aim to investigate valuable energy efficient guidelines for designers to promote IH steam generators integration in the medical sterilisation. To do so, we conduct an energy flow analysis based on a process-oriented decomposition. We then detail the previously identified guidelines through a review of the literature on IH-based liquid heating and analyse them throughout the paper. Many key points protrude therefrom: "inductor-susceptor/water" interactions are decisive especially susceptor shapes. A package of susceptor shapes exposed in this paper can be considered. Back heat transfer from the susceptor to inductor is important too. Frequency and turbulence has opposite effects, so should be given the utmost attention. Inductor losses need to be reduced via coil wrapping, water cooling, and multi-coil design for high powers. The energy efficient design of the susceptor includes stray magnetic fields, geometry of the susceptor, skin depth, and the effect of electromotive force due to eddy currents. Susceptor-inductor coupling is relevant too. Finally, the optimisation of thermal transfer to water involves insulation, frequency, discharge losses, turbulence and susceptor shape. Based on these parameters, good designs can be put forward to launch prototypes and explore fully IH opportunities in this field for more energy efficient sterilisers.

1 Introduction

Saturated steam sterilisers (big autoclaves) are one of the most energy consumers in hospitals (up to hundreds kilowatts at three-phases) due to the use of indirect resistance heating. Hence, all the professionals in the field are concerned by developing new energy saving solutions. Induction heating (IH) could be one of them considering its proven potential in industrial applications such as steam generation and pasteurisation [1], [2]. Hitherto, there is no indication about IH-steam generation for medical sterilisation in comprehensive references. A notable attempt was conducted by Kameda et al. for small top table autoclave for dentistry [3].

Thus, it appears that the potential of IH-based steam generators (SG) for this field has not been fully explored. Moreover, the application of IH-SG cannot ensure the energy savings expected unless it is well designed. For all these reasons, we identify and present in this paper, a package of guidelines to help designers develop energy-efficient steam generators for medical sterilisers.

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In simple terms, World Health Organization states: "sterilization is the elimination of all disease-producing microorganisms" [4]. Among all medical sterilisation techniques, saturated steam is still the dominant mode due to its effectiveness, safety, rapidity, low-cost and relative simplicity compared to other techniques.

Steam generation in big autoclaves is by default produced by joule heating in resistive elements. These are commonly in U shapes made of Nichrome wire. They are coated by an insulator powder such as magnesium oxide (MgO) and the sheath is made by a stainless steel alloy tube. Therefore, the heat is indirectly transferred from resistances to protecting tube in contact with water via MgO powder which meanwhile ensure electrical insulation. Resistive heating elements counts for 75% to 95% of autoclave power rating. Figure 1 displays an overview of a big autoclave and its main components.

Figure 1. Horizontal steam steriliser (big autoclave): (a) outside front view; (b) inside front view; (c) steam generator; (d) resistive heating element.

On the other side, induction heating (IH) is performed through 2 main stages:

1. Heat generation by an inductor in a medium workpiece called "susceptor" via 2 simultaneous processes:
1.1 Eddy currents process through 3 successive steps: electromagnetic induction, ohm effect and joule effect.
1.2 Heat generation by hysteresis.
2. Heat transfer from the suceptor to water.

2 Methods

In this study, we aim to identify valuable energy efficient guidelines for designers to promote the integration of IH in this area. To do so, we rely on a novel analytic method developed by Jemmad et al. [5]. Based on energy flow in Figure 2, we firstly decompose the whole process to main sub-processes starting from inductor –downstream the inverter stage–. The decomposition matrix containing energy efficiency key points is given in Table 1. Secondly, we proceed with a review of fluid heating literature and subject-related equations to draw up consequent guidelines to be applied for the IH-SG design. Energy efficiency measures are various and not applicable at once. The design of the susceptor is critical to the selection of the solution package. The first section presents the state of art of susceptor designs and discuss inductor –susceptor interactions key points to consider at the beginning of any study.

Then inductor design is discussed as its optimisation enhances the magnetic flux to be delivered to susceptor. Thereupon, the induction process begins in the susceptor body and leads at the end to Joule heating process via Ohm effect process. Since they are inextricably related, this section deals with the 3 processes at once. For more comprehensiveness in analysis, all parameters involved therein are expressed in one equation. Besides, heat production by hysteresis is overviewed. Finally, heat transfer optimisation between susceptor and water is investigated.

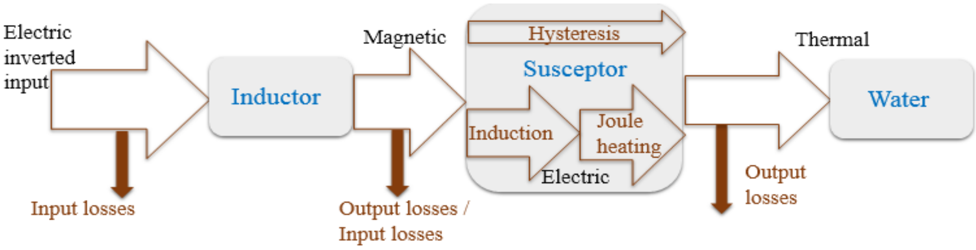

Figure 2. Energy flow and conversions processed in an IH-SG.

Table 1. Energy saving key points for design of an IH-SG for medical sterilisers.

<table>
<tr><th colspan="4" rowspan="2">Design</th><th colspan="3">Energy efficiency</th></tr>
<tr><th>Input losses</th><th>Energy conversion</th><th>Output losses</th></tr>
<tr><td rowspan="6">Induction heating system</td><td colspan="3">Inductor-susceptor/water Interactions</td><td colspan="3">- Inductor-susceptor: combination types and susceptor shape
- Inductor-susceptor: Susceptor back heat transfer to inductor
- Inductor-susceptor/water: Optimise parameters of opposite effects: frequency and turbulence.</td></tr>
<tr><td>Inductor</td><td colspan="2">Electric → magnetic</td><td>- Reduce losses of: high resistance
- Use multi-coil for high power.</td><td>Inductance</td><td>- Coupling inductor-susceptor
- Reduce magnetic stray fields.*</td></tr>
<tr><td rowspan="4">Susceptor/ water</td><td rowspan="3">Magneto-electric → Thermic: Eddy currents</td><td>Induction</td><td>Reduce heating time by increasing frequency.</td><td>Induced electromotive force (emf)</td><td></td></tr>
<tr><td>Ohm effect</td><td></td><td>Enhance eddy currents intensity by optimising susceptor resistance R_S</td><td>Eddy currents back-emf effect losses.</td></tr>
<tr><td>Joule effect</td><td></td><td>Optimise heat power generation.</td><td rowspan="2">Reduce heating time
Reduce thermal losses: insulation, discharge losses,
heating uniformity.</td></tr>
<tr><td colspan="2">magnetic→ thermic (Hysteresis)</td><td></td><td>No optimisation.</td></tr>
<tr><td colspan="7">*These guidelines are also available as input losses of induction process</td></tr>
</table>

3 Inductor-susceptor/water interactions

3.1 Inductor-susceptor combination types

Water is normally diamagnetic. To heat it, the indirect IH method is used through a conductive material, the susceptor. Graphite and ferritic stainless steel are preferred. Whilst the common inductor design is a multiturn and helical-shaped copper coil [6], susceptor designs are varied in industrial applications. Therefore, a preview of all available schemes should be conducted to ensure the best susceptor shapes. Altintas and Karahan summarize water heating by susceptors under 2 groups as illustrated in Figure 3 [7]. Table 2 summarizes all practiced types of inductor-susceptor combinations.

3.2 Susceptor shape types

This section introduces the various susceptor shapes experienced in IH-SG under floating and pool types.

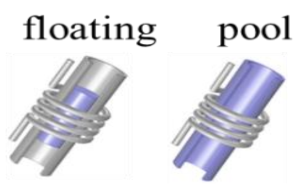

Figure 3. IH susceptor types by Altintas and Karahan: floating & pool [7].

Table 2. Practiced types of inductor-susceptor combination in IH for steam generation.

<table>
<tr><td>Floating type</td><td colspan="3">Susceptors in the form of various geometric forms such as rods, balls, discs, cylinders, rolls, bands etc. are immersed in water container.</td></tr>
<tr><td rowspan="4">Pool type</td><td colspan="3">Water flows through susceptor in form of tube (generally a helical pipe).</td></tr>
<tr><td>Classic (coreless)</td><td colspan="2">Tubes are heated by induction, then heat is transferred to water.</td></tr>
<tr><td rowspan="2">Magnetic core</td><td>Concentric design</td><td>Inductor and susceptor coils have the same core.</td></tr>
<tr><td>Rectangular design</td><td>Inductor and susceptor are wound on 2 separate sides</td></tr>
</table>

3.2.1 Floating-type susceptors

Balls: an example of this scheme was introduced in a Russian patent. Figure 4 illustrates metal balls contained in locking grids [8].

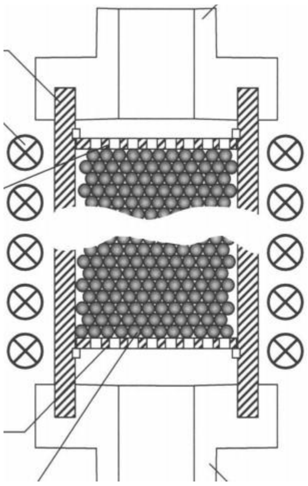

Figure 4. Floating-type susceptor: balls [8].

Cylinder: Kuwata et al. used cylinders of carbon ceramics with 90 mm in diameter and 90mm in height. These cylinders contain 14 holes of 10 mm in diameter to increase its heat exchanging area. All are inserted into the Teflon pipe as shown in Figure 5 [9].

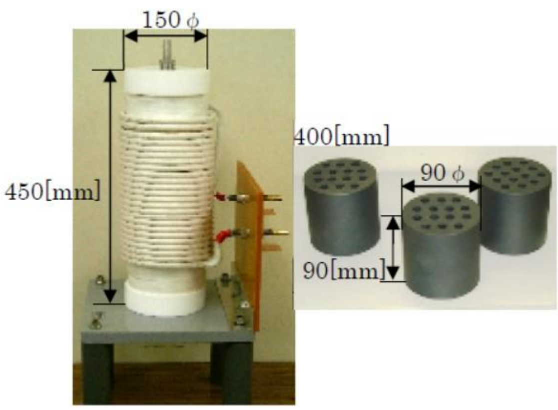

Figure 5. Floating-type susceptor: cylinders [9].

Roll: magnetic plate are rolled to a cylindrical shape. Figure 6 displays a sample experienced by Kuwata et al. in the form of a waved magnetic stainless plate of 0.3 mm in thickness wound to a cylindrical shape [9].

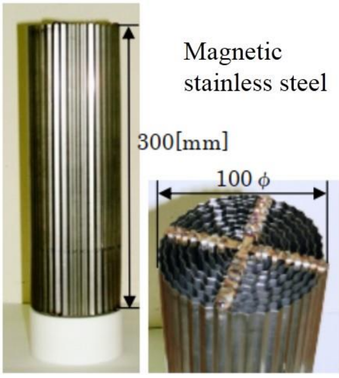

Figure 6. Floating-type susceptor: roll [9].

Hollow Rods/ straight pipes: this type was used by "DHF induction" company based on straight pipes arranged with non-contact and immersed in a tank as shown in Figure 7 [10]. Pipes or hollow rods may also be non-immersed, in which case they need insulation as the water is flowing through only.

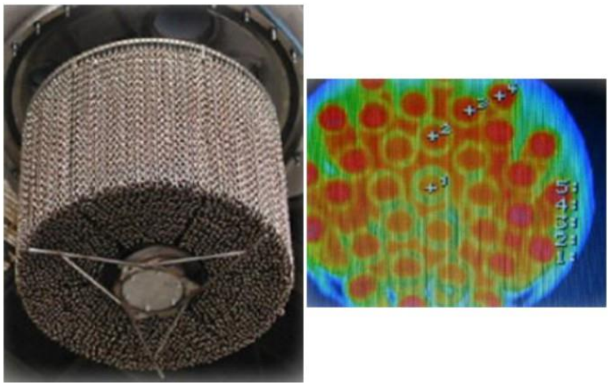

Figure 7. Floating-type susceptor: hollow Rods/ straight pipes [10].

Discs: Many materials have being experienced for discs. Figure 8 displays a quartz glass containing 41 magnetic stainless steel discs stacked horizontally that was used by Tomita et al. as susceptors. Each disc has a hole of 20mm for steam path [11]. Lanthanum strontium manganite (LSMO) [(La,Sr)MnO_3] –an oxide ceramic– was selected by Takasago Industry Co., Ltd for the superheated SG developed for ceramics degreasing [12]. Figure 9 presents the prototype of the IH-superheated SG.

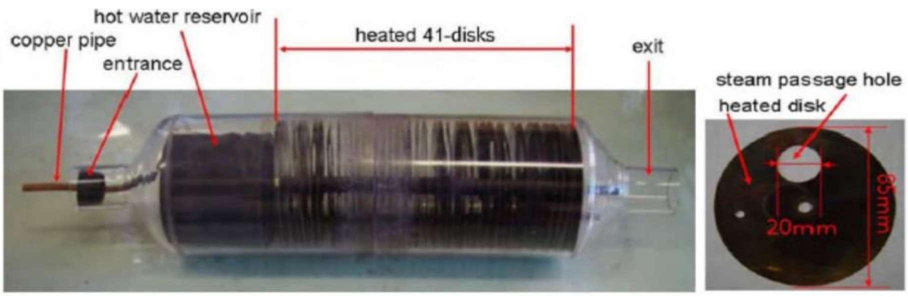

Figure 8. Floating-type susceptor: magnetic stainless steel discs [11].

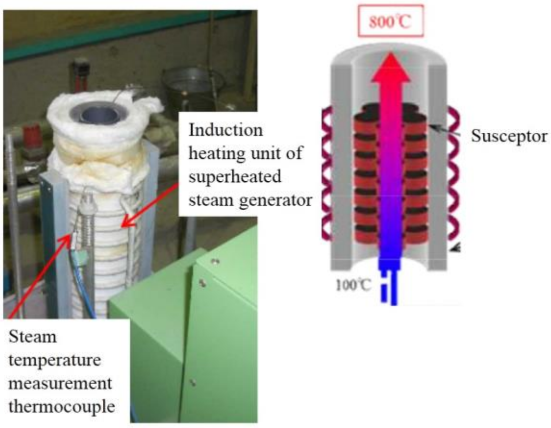

Figure 9. Floating-type susceptor: carbon discs [12].

Band: Makimura et al. and Tomita proposed magnetic stainless steel band twisted into double spiral shape as represented by Figure 10 [13], [14]. This design has been shown to be more efficient than discs experimented previously by Tomita et al.

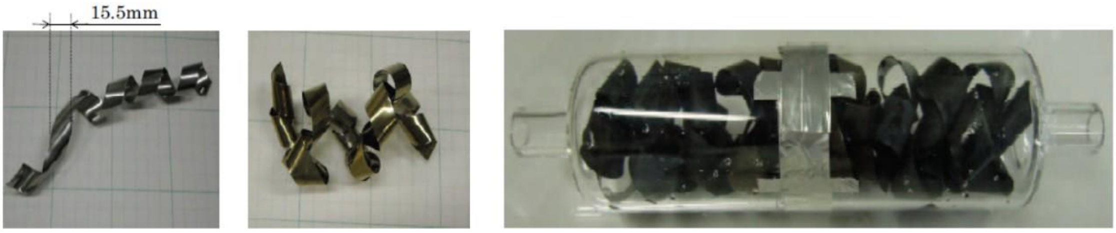

Figure 10. Floating-type susceptor: band [13], [14].

3.2.2 Pool-type susceptors

Classic (coreless): it is the standard scheme where the inductor is wound around the susceptor consisting of a tube or pipe inside which the water or fluid is flowing. Figure 11 displays the picture and the layout of an induction coil inducting a 316L stainless steel pipe designed for coconut juice pasteurisation [15].

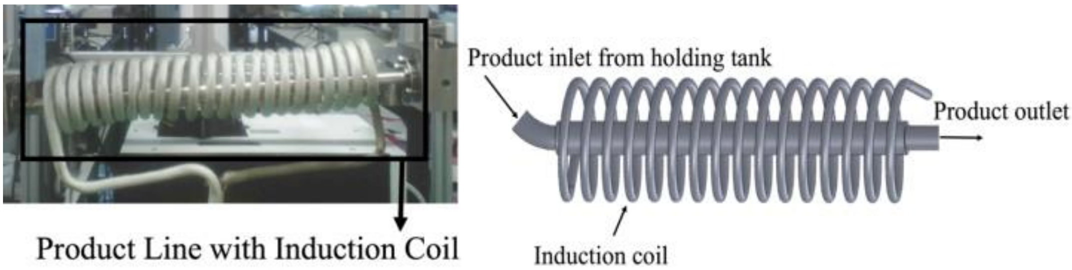

Figure 11. Pool-type susceptor: classic (coreless) [15].

Magnetic core - rectangular design: a rectangular magnetic core is linking the inductor to susceptor mounted on the other side of the transformer. In the example illustrated by Figure 12, the susceptor consists of a short-circuited stainless steel tube (SS 304) through which the milk is flowing for pasteurisation [16].

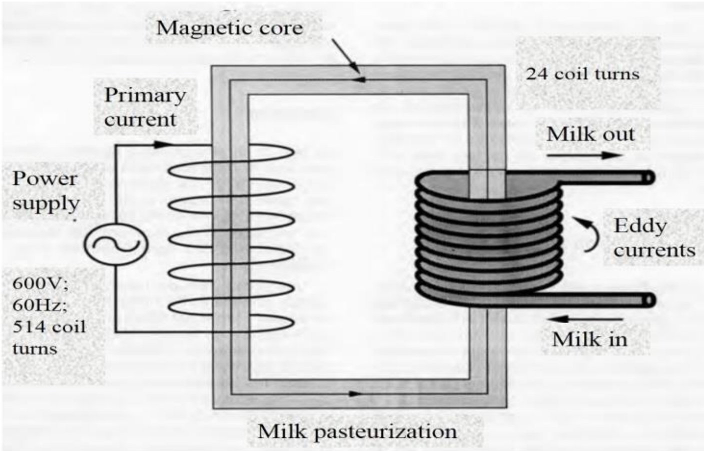

Figure 12. Pool-type susceptor: Magnetic core - rectangular design [16].

Magnetic core - Concentric design: the inductor is wound inside the susceptor around a magnetic core. We cite 2 commercialised products under this class: DIFHEMI heaters and UPSS W Series. DIFHEMI heaters use a 3 phases dry transformer-like design where stainless-steel tubes are short-circuited. UPSS W Series are designed upon 2 features: 3-phases Y-shaped core and circular core by each phase. Figure 13 and Figure 14 illustrate respectively both designs [1], [2].

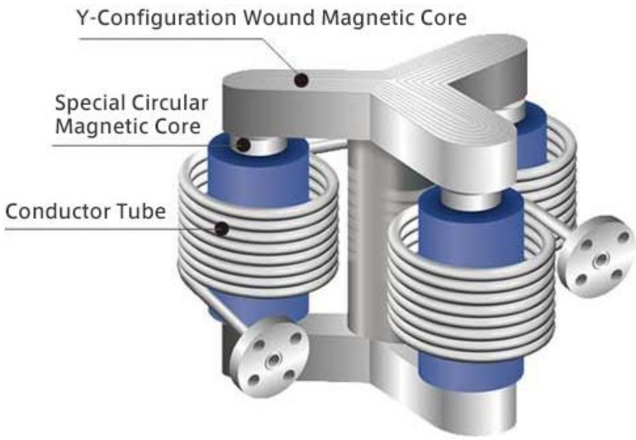

Figure 13. Pool-type susceptor: Magnetic core - Concentric design, UPSS W series example [1].

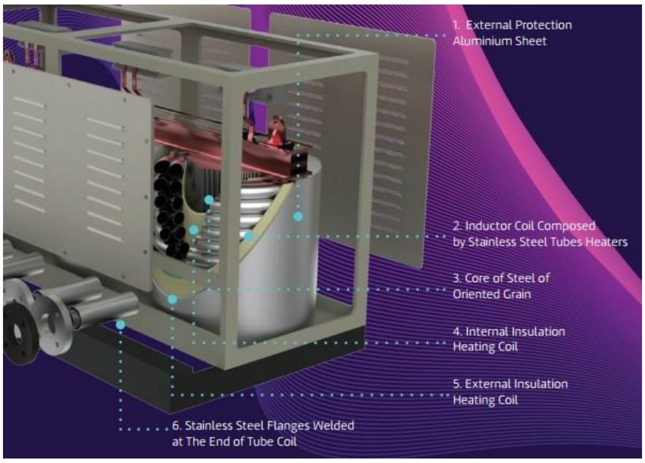

Figure 14. Pool-type susceptor: Magnetic core - Concentric design, DIFHEMI heaters example [2].

3.3 Susceptor back heat transfer

Susceptor back heat transfer: Inductor coil might be also overheated by thermal convection and radiation through heated susceptors. A good heat insulation must be carried out between susceptor and inductor.

3.4 Parameters of opposite effects

3.4.1 Frequency

It is well known that frequency enhances induction heating by maximizing emf, increasing the Joule effect through skin depth, and increasing hysteresis power. However increasing frequency leads to less heating uniformity and raises the inverter cost significantly. Power inverter switching losses are also another limitation [17], [18]. Therefore, a thorough study should be carried out to choose optimal frequency.

3.4.2 Turbulence

Increasing turbulence may have a positive effect on fluid heating uniformity while being unfavourable to heating time. Susceptor shapes have a significant effect on turbulence, hence they must be examined on this point before adopting any of them. Section 8 provides further details on both turbulence effects.

4 Inductor energy-efficient design

4.1 Inductor input losses

Inductor resistance and temperature: IH-coil might be overheated by the coil joule heating depending on its current. Induction coil is made of an electrolytic copper pipes. In high power models, inductor pipe is internally water cooled to ensure low resistance and lessen temperature rising effect on resistance [6], [14], [19], [20]. Multi-coils: For high current intensity applications, it is better to divide the available power on many coils. The current intensity by coil will decrease and tube thickness. Thus, cooling requirements are reduced.

4.2 Inductor energy conversion

Since $\phi=Li$, coil inductance L stands as an energy efficiency indicator of magneto-electric conversion. Inductance is improved based on coil geometry and core magnetic permeability. Practically, increasing the number of turns or reducing length is ensured by wire tight wrapping. It helps also reducing vibration [6], [21], [22].

4.3 Inductor output losses

4.3.1 Inductor – susceptor coupling

Horizontal coupling: 86 % of the heating is located nearby the coil and decreases exponentially with the distance from the coil [22]. In a coil, the magnetic field density is higher near to windings. Hence, susceptors positioned at this position benefit from maximized power heating. On the side of vertical coupling, it is found in practice that the maximum joule heat observed is the central point of the coil [22-25].

4.3.2 Magnetic stray fields

A part of the magnetic flux produced is lost in the form of stray fields that are flowing far away from the susceptor. Two techniques are followed in industry and domestic applications: Flux controllers using soft-magnetic materials and Transformer core. The latter corresponds to magnetic core pool type and has a safety side as it lessens magnetic fields in the surroundings [20], [26].

5 Susceptor heat power expression

Back to susceptor shapes exposed in section 3.2, the most applicable ones are hollow rods and helicoidal tubes. These can be then modeled as a coil of N_S turns (a hollow rod is approximated by a coil wrapped very tightly). As explained in section 6.1, shapes such as solid discs are not discussed. The magnetic flux ϕ over a cross-section S_{sus} induces an "applied" electromotive force (emf):

$$\overline{E} = -N_S \frac{d\overline{\phi}}{dt} \tag{1}$$

Let

$$\overline{\phi} = \sqrt{2}\phi e^{j\omega t} \tag{2}$$

Then, emf in rms value is expresses as:

$$E = N_S \omega\phi = 2\pi f N_S \phi = \sqrt{2}\pi N_S f B_m S_{sus} \tag{3}$$

Where B_m is the peak value of magnetic flux density, and f is the power frequency. The induced electromotive force (emf) generates in a susceptor an amount I_{ed} of eddy currents according to ohm law. However these eddy currents induce by turn a magnetic field intensity H_{ed} that opposes them. According to Ampere's law, the magnetic flux density over a susceptor of length h and magnetic permeability μ_{sus} is then:

$$B_{ed} = \mu_{sus} H_{ed} = \mu_{sus} \frac{I_{ed}}{h} \tag{4}$$

The last induces a back-emf. So finally, the susceptor is subjected to the effective emf E':

$$E' = E - E_{ed} = \sqrt{2}\pi N_S f S_{sus} B_m - \sqrt{2}\pi N_S f S_{sus} B_{ed} \tag{5}$$

From (3), (4) and (5), we get:

$$E' = \sqrt{2}\pi N_S f S_{sus} (B_m - \mu_{sus} \frac{I_{ed}}{h}) \tag{6}$$

Let Rs be the equivalent resistance of all paths followed by eddy currents. The power amount dissipated as heat is then:

$$W = \frac{E'^2}{R_S} \tag{7}$$

Let ρ be the susceptor resistivity, l and S_{ed} respectively: eddy currents path length and cross-section area: $R_s = \rho l / S_{ed}$, then:

$$W = \frac{(\sqrt{2}\pi N_S f S_{sus})^2}{\rho \frac{l}{S_{ed}}} (B_m - \mu_{sus} \frac{I_{ed}}{h})^2 \tag{8}$$

To ensure energy efficiency, heating time and heat power need to be optimised. Equation 8 shows that the heat power depends at the first level on magnetic flux density and frequency which are affected by inductor design. It depends equally on back-emf induced by eddy currents, susceptor cross-section area and number of coil turns. Then at a second level, it depends on susceptor cross-section area and eddy currents path length.

6 Susceptor energy-efficient design

6.1 Heating time

The faster is a susceptor heated, the lower is the energy consumed. Generally, small or thin parts heat more quickly than large thick parts [27]. Also, Time heating decreases with frequency increase: in an IH-reactor of high-temperature epitaxial growth system, Mei et al. report by simulation, that faster heating rate can be obtained by increasing heating frequency [23].

6.2 Eddy currents path resistance

6.2.1 Resistivity and path length

Many materials can be used for susceptors in water heating but graphite and stainless steel are the most common ones. Stainless steel is particularly preferred for pool types [19], [28-31]. Susceptor design should take advantage of big lengths to increase resistance. E.g. susceptor of bigger coil radius will provide bigger path length for eddy currents.

6.2.2 Cross section area, skin depth and thickness

In their experience, Park et al. get a higher efficiency by changing the susceptor shape from a cylinder to a tube. This result stems from inductive reactance reduction and thus the electrical resistance was improved [24]. In more detail, some parameters are found by practice to be more influential on heating. These parameters are implied in Equation 7 as they depend on susceptor geometry and composition. The square effect of frequency is partially related to skin effect. By increasing frequency, the skin depth is reduced which increase eddy currents path resistance and therefore generates more heat. Thus it is more enlightening to express it. Let δ be the skin depth:

$$\delta = \sqrt{\frac{\rho}{\pi f}} \tag{9}$$

Then we can write from (8):

$$W = \frac{2\pi N_S^2 f S_{ed} S_{sus}^2}{l} \frac{\pi f}{\rho} (B_m - \mu_{sus} \frac{I_{ed}}{h})^2 \tag{10}$$

$$W = 2\pi N_S^2 f \frac{1}{\delta^2} \frac{S_{ed} S_{sus}^2}{l} (B_m - \mu_{sus} \frac{I_{ed}}{h})^2 \tag{11}$$

Moreover, Park et al. report that skin depth effect is relative to susceptor thickness unlike the common misunderstanding that only skin depth counts. Particularly, the maximum heat is achieved at critical thickness t/δ =0.1. The critical thickness performance is due to the best compromise between eddy currents intensity and their path resistance [24]. Since path section area S_{ed} enfolds the susceptor thickness *t*; we consider the example of a hollow rod as illustrated in Figure 15 to represent critical thickness in the joule heat expression.

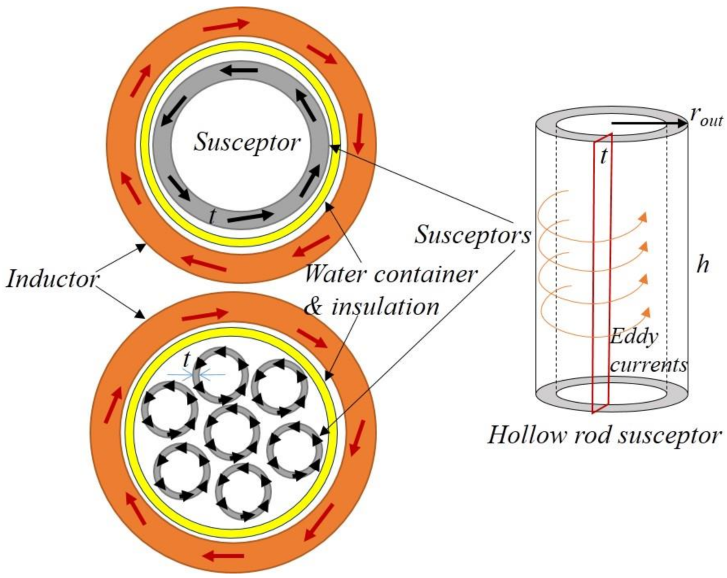

Figure 15. Eddy currents paths in a susceptor of hollow rod.

Applying that $S_{ed} = t.h$, $S_{sus}=\pi r^2_{out}$, and $l=2\pi r_{out}$; we get from (11):

$$W = \pi^2 f N_S^2 (\frac{t}{\delta})^2 \frac{h r_{out}^3}{t} (B_m - \mu_{sus} \frac{I_{ed}}{h})^2 \tag{12}$$

Equation 12 displays the t/δ term representing the critical thickness effect on heating enhanced by power 2. Since resistivity, permeability and geometry are slightly scalable, designers should modify frequency to keep thickness skin depth reach critical thickness for maximal heating. Besides, Equation 12 enlightens the geometry contribution to rise heating. A small thickness compared to length ($h>>t$) leads to more heating regardless of h to r_{out} proportion.

6.3 Mitigation of eddy currents back-emf

The effective emf is opposed by the back-emf induced by magnetic flux ϕ_{ed} generated by eddy currents via a susceptor inductance L_{sus} ($\phi_{ed} = L_{sus} I_{ed}$). If I_{ed} is reduced; the heat energy will be reduced too. Hence, L_{sus} need to be lessened as much as possible. If we take, for example, a susceptor in the form of a long coil or a hollow rod (2 potential forms of practice); the inductance can be expressed as for a solenoid:

$$L_{sus} = K_N \frac{V_{ed}}{V_{sus}} \mu_{sus} N_S^2 \frac{S_{sus}}{h} \tag{13}$$

K_N is the coefficient of Nagaoka, V_{ed} is the susceptor volume to be heated by eddy currents and V_{sus} is the whole volume of susceptor. K_N is minimal if $h<D$ where D is susceptor diameter [32].
From Equation 13, we deduce that to reduce L_{sus}, rods or coils need to be as long as possible without reducing diameter (susceptor cross-section area S_{sus} must not be reduced). But still, the number of turns in length direction depends on length h. In case of pipe coils, to increase length without adding coil turns, wrapping must not be tighted.

7 Heat generation by hysteresis

Practically, hysteresis occurs only in metals such as steel. Moreover, many authors estimated that the amount of energy generated by hysteresis in induction heating, does not exceed 10% compared to eddy currents [21], [28], [29], [33]. Considering that flux density, frequency, and susceptor parameters are already imposed by eddy currents process; there is no additional optimisation to expect at this stage.

8 Heat transfer from susceptor to water

8.1 Water heating time

8.1.1 Susceptor shape effect on heating time

Susceptor shapes like large solid discs should be avoided as they obstruct fluid flowing and causes a longer heating duration [13], [22], [34].

8.1.2 Turbulence effect on heating time

In their experimentation of an air heater pool-type prototype, Unver et al. indicated that they avoid turbulence as it increases the duration of air passing which has a negative effect on heat transfer [35].

8.2 Water heating losses: insulation

Heat losses can be avoided with an appropriate insulation of steam tubes or containers [34], [35]. A variety of materials has been used for that purpose including ceramic and borosilicate glass among others [13], [24].

8.3 Water heating losses: discharge losses

In big size systems, obstacles like large solid discs may cause significant losses due to friction-discharge losses [35].

8.4 Water heating losses: heat uniformity

If there is low thermal transfer, the susceptor temperature need to be elevated at a higher level in order to reach water desired temperature. Hence, temperature uniformity is recommended to enhance thermal transfer efficiency.

8.4.1 Input frequency effect on heat uniformity

According to Mei et al, frequency also has an effect on temperature uniformity between the transducer and the workpiece. In their case, Mei et al. found that it is recommended to keep the frequency in the middle range, not too large or too small. Their results announce 17.5 °C difference in temperature for frequencies between 10 and 25 kHz, while 50 kHz induces 50 °C of difference [23].

8.4.2 Susceptor shape effect on heat uniformity

Additionnally, round parts are preferable than sharp edges shapes where the current density is higher and therefore creates difference in heating level. Immersed hollow shapes as in Figure 7, bring the additional advantage of heating water from 2 sides especially for small thicknesses. Temperature difference is therefore negligible.

8.4.3 Turbulence effect on heat uniformity

For their floating-type SG, Nakamizo et al. reported that turbulence increases fluid heating uniformity [36]. They experienced that 2 carbon ceramic cylinders as in Figure 5, generate more turbulence than one cylinder [36].

9 Concluding remarks

An energy saving oriented design should take in account the guidelines explored in the previous sections. At a first stage, the interactions inductor-susceptor are the first element to check. It implies the selection of the advantageous inductor-susceptor combination type alongside with susceptor design and the adequate input frequency. On the one hand, inductor-susceptor shape is decisive from two perspectives: conformity with the steriliser design and energy efficiency enhancement. On the second hand, increasing frequency plays a key role in IH energy efficiency. Firstly, it reduces heating time. And secondly, it augments induced electromotive force in the susceptor and significantly increases the eddy current path resistance due to the skin depth effect. However, the frequency cannot be increased indefinitely because it reduces the uniformity of heating and increases the cost and switching losses of the inverter. After carrying out interactions study, inductor and susceptor design features are set up. Regarding inductor, its coil inductance need to be improved by tight wrapping. Its losses can be reduced by water cooling, good insulation from susceptor and multi-coil design for high powers.

Thereafter, susceptor design is to be set. Susceptors are preferred to be small or thin and long. Generally, small or thin parts heat more quickly than large thick parts. Big susceptor lengths can help mitigating back electromotive force losses induced by eddy currents. Vertical centering of susceptor in floating-type designs and horizontal proximity optimise energy transfer between inductor and Susceptor. Also, some effort should be undertaken to limit magnetic stray fields which help boost applied magnetic field. Flux controllers and magnetic core designs under pool type can be considered for that purpose. Finally, thermal transfer from the susceptor to water can be enhanced by path freeing to avoid discharge losses, ensuring insulation, and heating uniformity via turbulence and relatively reduced frequency. Round, hollow and thin susceptors are favourable for that purpose as well as for heat time reducing. Optimal turbulence should be set to ensure heating uniformity without compromising heating time. Figure 16 summarizes the main key points about energy efficiency oriented design of IH steam generators for medical sterilisers.

The identification model used helped us to extract appropriately and systematically interesting energy-efficiency guidelines for induction heating based steam generator design. The selection of an advantageous "inductor-susceptor/water" combination is decisive. Frequency and turbulence have opposite effects, so should be given the utmost attention. Inductor losses are reviewed by discussing coil wrapping, water cooling, and multi-coil design for high powers. Whereas susceptor energy-efficient design involves, magnetic stray field, susceptor geometry, skin depth, and eddy currents back electromotive force effect. Susceptor-inductor coupling is relevant too. Finally, thermal transfer optimisation from susceptor to water involves insulation, frequency, discharge losses, turbulence and susceptor shape. Based on these parameters, good designs can be put forward to launch prototypes and explore fully IH opportunities in this field for more energy efficient sterilisers.

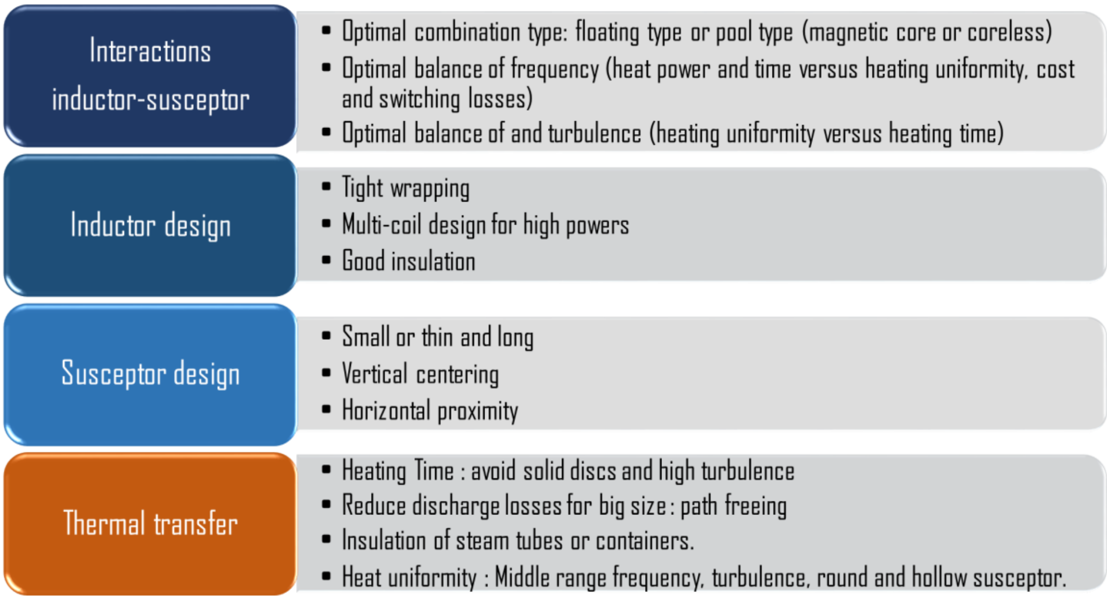

Figure 16. Summary of key points on energy efficiency oriented design of medical sterilisers IH-SG.

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