Energy Efficient Autoclaves - Misconceptions and Misunderstanding

Gareth West, Astell Scientific

Autoclave manufacturers are keen to espouse their green credentials and inform us of how their devices use less energy, but is it possible to make the radical savings that are claimed? Not always. Sterilisers are finely-tuned devices, and producing maximum results with minimum impact is often a question of balance.

To understand the energy efficiency capacity of autoclaves it is crucial to begin by pinning down the essentials: what an autoclave must be to work as it should.

Back to basics - How does an autoclave work?

An autoclave is essentially a highly refined tool built for a specific job: sterilisation. The goal is to kill all biological life and deactivate biological agents placed within autoclaving chambers, typically by raising their temperature to 121°C for 15 minutes or more [1,2] (although shorter processes at higher temperatures are also possible [3]). Reliably maintaining and measuring these temperatures is essential for achieving and validating sterilisation, and fluctuations below the sterilisation temperature invalidates the process, requiring it to be repeated.

For sterilisation to be effective, a fluid substance must fill the autoclave chamber and transfer heat to everything within it. Frequently, this means using steam with specific qualities. Pure steam gas that contains no liquid water - known as dry steam - is a poor conductor of heat and ineffective at steam sterilisation [4]. Dry saturated steam that carries 5% by mass of liquid water (or has a dryness fraction of 0.95) is the most effective fluid for transferring heat to a load within an autoclave. Any dryer and the heat is not effectively transferred to the load, any wetter and the loads will be sodden.

As Anders Celsius eternally reminds us, the boiling point of water is 100°C at standard temperature and pressure (STP), so to reach minimum sterilisation temperature autoclaves must create conditions that make the boiling point of water higher. By raising the pressure in a sealed environment, the boiling point of substances within that environment is also raised *(see Figure 1)*. For example, raising the pressure within an autoclave chamber to 2.068 Bar(a) will cause water to boil at 121°C, while increasing pressure to 2.896 Bar(a) will create an environment in which water boils at 132°C.

To sterilise effectively, both a sealed pressurised environment greater than 2.068 Bar(a) and a temperature of greater than 121°C are required. An autoclave must be able to both withhold these internal temperatures and pressures, and generate dry saturated steam from water (usually via electrical energy).

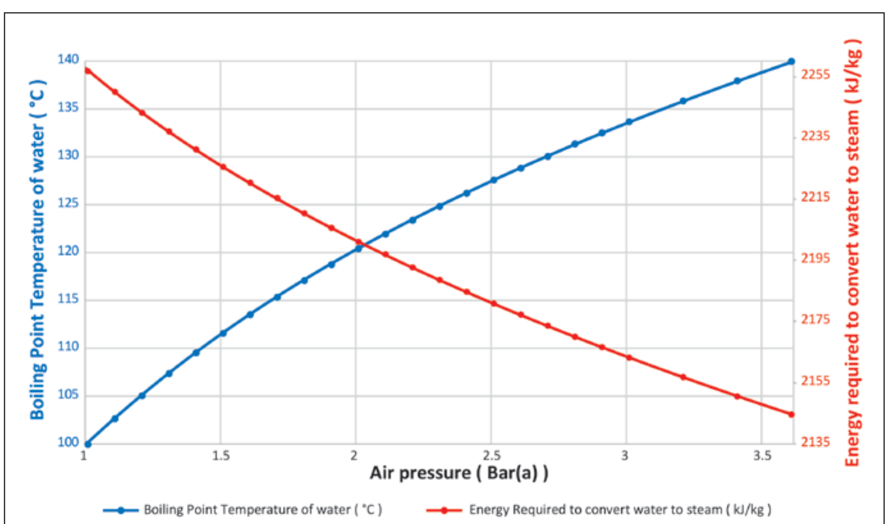

Figure 1. The effect of increasing air pressure on the boiling point of water, and on the energy required to convert water to steam.

The invariability of steam generation.

Dry saturated steam generation from water is an inevitable starting point for investigating autoclave energy use. At STP, water requires 2,257 kilojoules of energy per kilogram (kJ/kg) to become dry saturated steam. If the environment in which the steam is produced is at higher pressure, the quantity of energy needed to convert water to steam is less. At the minimum sterilisation temperature and pressure (121°C and 2.068 Bar(a)), 2,201 kJ/kg are required to generate dry saturated steam from water. This process will create steam that will fill a 0.841m3 space per kilogram of water used. These are the physical, unchanging properties of H_2O, and provide the limitations on how energy efficient an autoclave can be.

In the hypothetical ideal autoclave (that wastes no energy) the initial volume of water used to generate steam is the only variable that affects energy consumption. The smallest possible volume of water in the steam generator provides the most energy efficient system – if water requires a specific quantity of kilojoules per kilogram to convert it to steam, the only way to reduce the energy usage is to reduce the mass (and volume) of water *(see Figure 2)*.

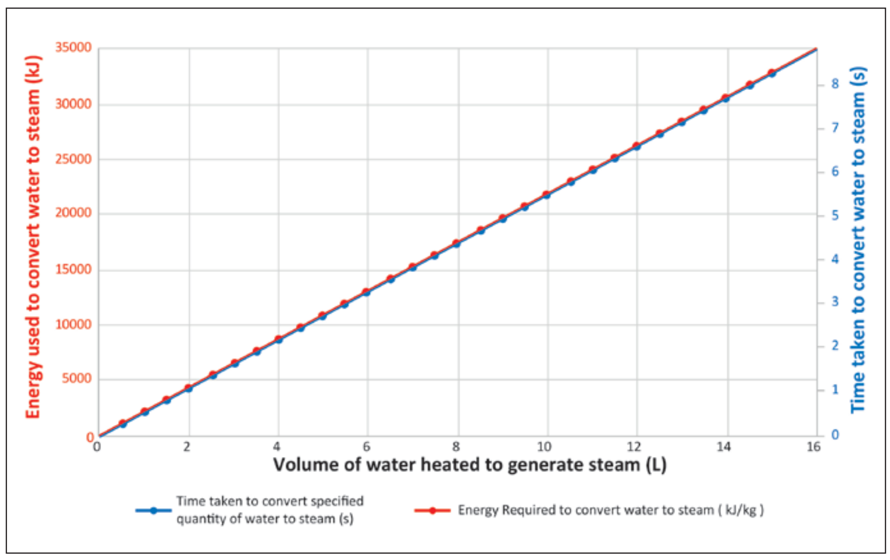

Figure 2. The effect of the volume of water heated to produce steam on energy consumption and time taken to convert water to steam (using a 4kW heating element at 2.068 Bar(a)).

There is often a misconception that, for electrical systems, using a smaller and lower wattage element will mean lower energy consumption. In truth, the same quantity of energy will be required to heat the water and produce steam, the process will just take longer *(see Figure 3)*. Given identical conditions, the longer water takes to boil, the greater its heat loss to the external environment. To generate the most energy-efficient steam for an autoclave, it is therefore essential to have the smallest possible water volume within the steam generator with the biggest possible heating element.

Working out the volume of steam required for sterilisation, and thus the volume of water, is unfortunately not as simple as calculating the air space available in the autoclave chamber. To reach and maintain the correct temperature throughout the autoclaving process, additional hot steam is added and cooled steam removed from the chamber to counter heat transfer. As such, it is the vessel that contains the autoclave chamber that has the potential for being the key source of thermal energy loss.

Keeping heat and pressure in one place: The Vessel

As the component that contains the autoclave chamber, the vessel is integral to maintaining necessary heat and pressure and must be designed accordingly. To retain pressure, materials with a high tensile strength are required - with variants of steel or aluminium alloys being popular choices. However, the thermal conductivity of these materials is high, facilitating heat transfer from the chamber - via the vessel - to the external environment.

Applying insulating material to the outside of the vessel is an effective method of reducing this loss, but a well-insulated vessel alone will not cool quickly when required - it will require a jacket. The jacket is a cavity between the vessel and insulation that can be flooded with steam or water, providing heating and cooling as required. Alongside allowing for vessel insulation, the jacket enhances chamber temperature control, decreasing the possibility of a failed sterilisation cycle and improving processing times. A failed sterilisation cycle is the greatest potential source of wasted energy, effectively doubling power consumption by necessitating a repeat cycle.

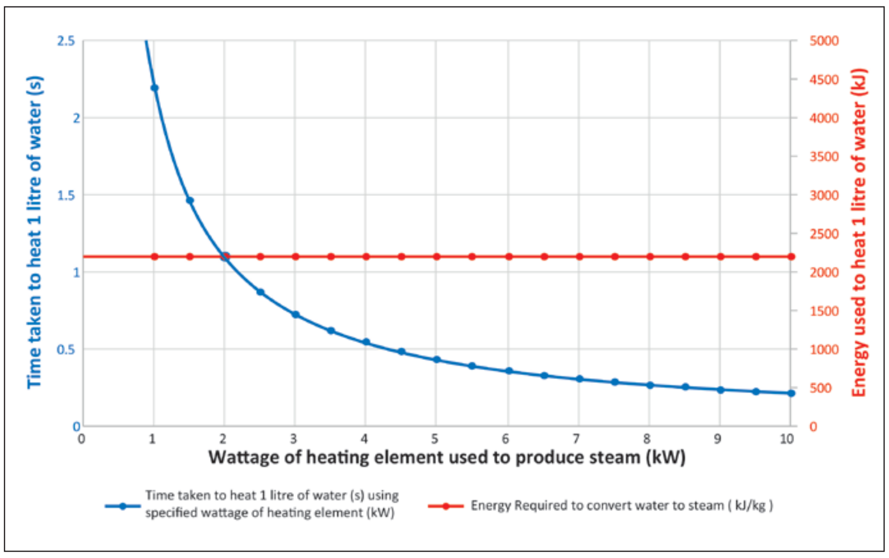

Figure 3. The effect of increasing the wattage of an autoclave water heating element on time taken to produce steam and energy used to produce steam (at 2.068 Bar(a)).

Although effective autoclaves are designed to maintain a constant temperature to avoid a failed cycle, there is one commonly overlooked attribute that can help mitigate this energy-intensive occurrence - thicker vessel walls. The thicker a vessel's walls, the greater its thermal mass. This thermal mass provides the vessel with greater ability to counteract temperature fluctuation, vastly reducing the possibility of a failed cycle. Thicker vessel walls can also retain higher chamber pressures, which provides additional energy-saving benefits.

A square hole or a round hole. Vessel and chamber shapes.

As gases exert forces equally in all directions, thinner-walled vessels are limited to a cylindrical shell structure to retain chamber pressures. While in top-loading autoclaves this design proves less detrimental, in front-loading devices such a design is a source of much wasted energy.

The functional sterilising area of a front-loading cylindrical-chambered autoclave can be simply described as a cuboid within the boundaries of a cylinder. This cuboid will always be 64% of volume of the cylinder, no matter the cylinder's size *(see Figure 4)*. As such, to fill a cylindrical autoclave can take up to 36% more steam, and therefore 36% more energy to generate that steam, than its cuboid equivalent. If the top of the cylinder is used for sterilisation, and the bottom section is filled to remove the air space, still 18% more steam is required to fill the curved sides. While octagonal-fronted shelving units attempt to better fill its circular face, the cylindrical chamber provides a challenge to maximise chamber space use.

With thicker walls able to withstand higher pressures, a chamber shape that provides even pressure distribution is less of a concern. Therefore, with thicker walls a more space efficient chamber and vessel shape can be used - the cuboid. Cube-shaped vessels, when sized and shelved correctly, can be filled with loads that leave minimal air space. As such, they require less steam to fill their chambers than their cylindrical equivalents - less wasted steam means a lower energy requirement.

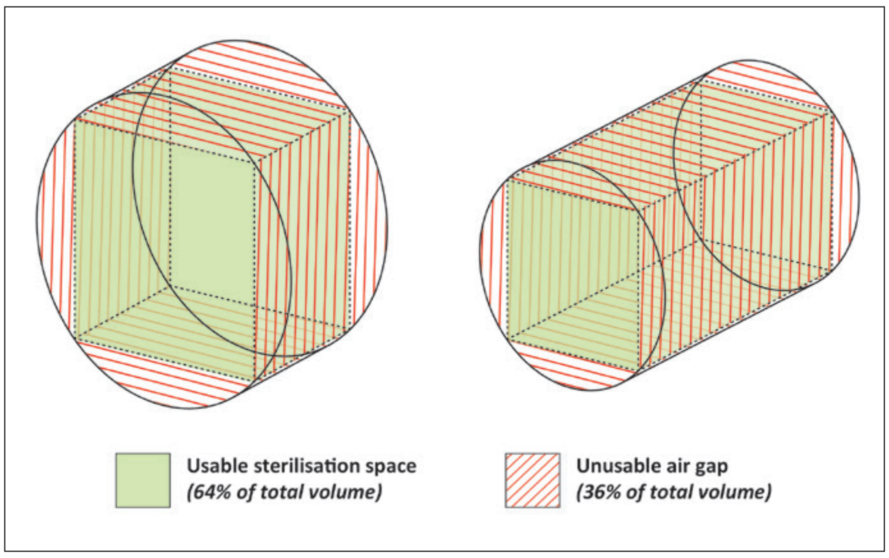

Figure 4. Geometry of a cylindrical autoclave chamber: Usable and unusable spaces.

A square peg in a square hole - Filling the chamber.

Unused energy-wasting space within an autoclave space can therefore be mitigated by the correct vessel and chamber shape. However, if the chamber is not filled, energy efficiency cannot be achieved. Potentially, the most important factor to make sterilisation energy efficient is to ensure the chamber is at its load capacity.

If the same quantity of materials are autoclaved in multiple loads, more energy will be used than if they are sterilised as one load. Furthermore, if an autoclave is run half-loaded, it cannot reach its full energy efficiency. As such, to be most energy efficient an autoclave should be designed specifically for the quantity of its load and the frequency of its use.

What is the most energy-efficient design of autoclave?

While rapid but minimal steam generation, vessel insulation, and chamber geometry all play a part in assessing autoclave energy efficiency, hardware qualities and specifications alone cannot provide the answer. The day-to-day use of the autoclave is a determining factor when calculating how energy efficient it actually is. Load type, volume, and post-sterilising condition, alongside the autoclave's operational frequency must be considered. Only by matching practical application with complementary hardware can the highest levels of energy efficiency be achieved.

So, in answer to the question "Which autoclave is the most energy efficient?" The answer is a somewhat unsatisfying "It depends".

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