Evaluating the Energy Efficiency of Autoclave Curing

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1. Abstract

This study investigates the energy efficiency of the autoclave curing process, defined as the ratio of useful energy delivered to the composite parts to the total energy input into the autoclave system. A Model-based System Engineering (MBSE) framework is used to track and then quantify the cumulative energy of the autoclave's components: thermal (composite parts, tooling, circulating gas, and autoclave shell), mechanical (vacuums, pumps, and fans), and electrical (computers and control units). Within this framework, composites process simulation software is used to perform detailed 1D analysis of the energy distribution, here applied to the autoclave in our CRN laboratory. The demonstrated approach can be readily applied to any autoclave system.

2. Introduction

Sustainability is an increasingly important consideration for all engineered products. In the case of composite aerospace products, the energy associated with their production is small compared to the energy savings due to weight reduction in service, even though the embedded energy in the raw fibre and resin is high [1]. However, a complete life cycle analysis should also evaluate the manufacturing process that converts the composite material into a finished product. In thermoset matrix composites an energy-intensive step is the curing of the matrix, which typically undergoes autoclave-based curing processes. In autoclave curing, the part is placed on a tool inside the vessel, typically pressurized to 100 psi and exposed to temperature cycles with a maximum temperature ranging from 120 to 200°C [2].

This curing process is best analyzed as a systems problem, and any variation in response in the curing cell can propagate through the entire process chain and affect the quality or property outcomes. In this work, a previously developed structured approach that defines the Material, Shape, Tooling, Equipment, and Process (MSTEP), is integrated into a Model-based System Engineering (MBSE) framework to analyze the thermal efficiency of the CRN autoclave (1.4 m x 1.8 m) [3]. This framework leverages computationally efficient simulations using the ORCA simulation framework [4], the results of which are then validated against experimental measurements.

3. Methods

3.1. Autoclave System Modelling

An autoclave system is a complex assembly of interdependent subsystems (Figure 1), which can be categorized into electrical, mechanical, and thermal subsystems based on their functionality, as shown in Table 1. The most important subsystem is the thermal system, as it directly governs the thermal history of the composite parts and therefore affects the production quality. This subsystem is a combination of the gas flow interacting with a complex network of discrete thermal masses and is enclosed by the autoclave shell. Next, the mechanical subsystems convert electricity into mechanical work (primarily the gas flow, but also other systems such as water cooling and vacuum) via an assembly of transmission components and actuators. Lastly, electrical subsystems provide the control and measurement capability for the whole system. They consume electricity but do not perform physical work nor generate significant heat.

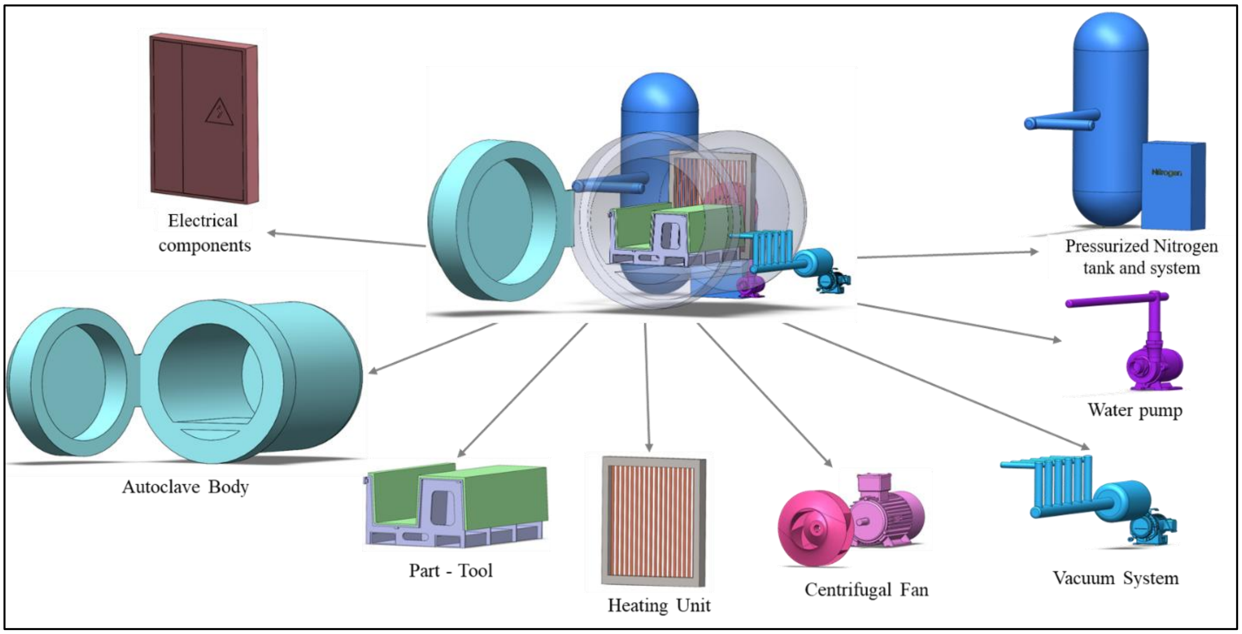


Figure 1: Autoclave functional subsystems breakdown

Table 1. Autoclave Subsystems and Components.

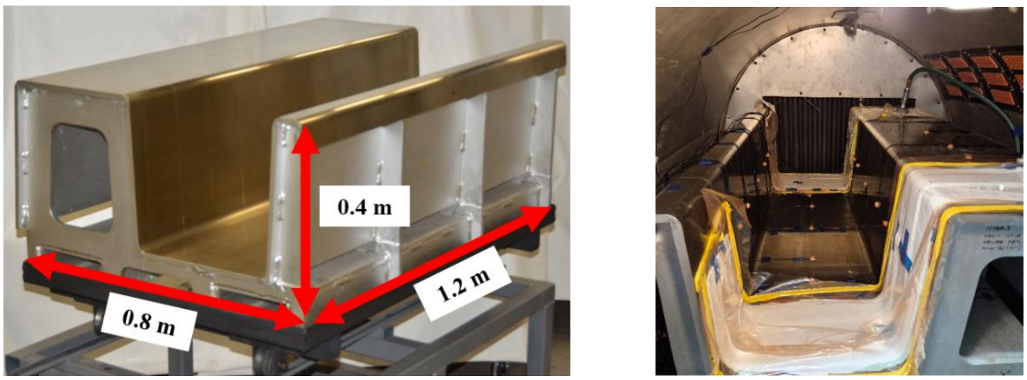
Subsystems	Components
Electrical	Computers, Programmable Logic Controls (PLCs), controllers
Mechanical	Vacuums, pumps, pressurized Nitrogen tank and system, fans
Thermal	Heating unit, thermal masses (composite parts, tools/moulds, racks, circulation gas, autoclave internal structures and shells)

To model energy consumption of the whole system, one must examine the instantaneous power demand of each subsystem, $\dot{E}_{subsys,n}(t)$, and integrate these values over the entire duration of the cycle (t_{total}) to obtain an accurate energy profile. The cumulative energy input of the entire autoclave, $E_{in,sys}$ in Joules, is then defined using the following integral:

$$E_{system} = \int_0^{t_{total}} \dot{E}_{system}(t) \cdot dt = \sum_1^n \int_0^{t_{total}} \dot{E}_{subsys,n}(t) \cdot dt \quad (1)$$

3.2. Experiments

The energy model of the CRN autoclave was validated against a two-hold cure cycle, where a full part-tool assembly is placed inside the autoclave. Approximately 0.6 kg of HEXCEL-8552 unidirectional carbon fibre prepreg was placed on a 400 kg Invar tool (Figure 2). This experiment served to validate the energy model to its full extent by accounting for the complex thermal interactions among the part-tool assembly, circulating gas, and the autoclave.



a. b.

Figure 2. (a) Image of the 400 kg CCMRD Invar tool with dimensions; (b) the part-tool assembly prepared with HEXCEL-8552 prepreg and vacuum bagged inside the CRN autoclave.

3.1. Equipment

The two main pieces of equipment used in this experiment were the CRN autoclave and an AEMC power and energy logger (Figure 3). The autoclave is 1.4 m in diameter and 1.8 m in length. The logger was attached to the main electric box to measure the overall power demand and thus the accumulated energy consumption.

a. b.

Figure 3. (a) Image of the CRN autoclave, manufactured by American Autoclave Co.; (b) AEMC Power and Energy Logger Model 103

3.2. *Measurements*

Infrared images were captured during heating experiments to identify localized hot spots. As shown in Figure 4, the external shell exhibits a non-uniform temperature distribution. These IR observations provided an empirical basis for the strategic placement of thermocouples (TCs).

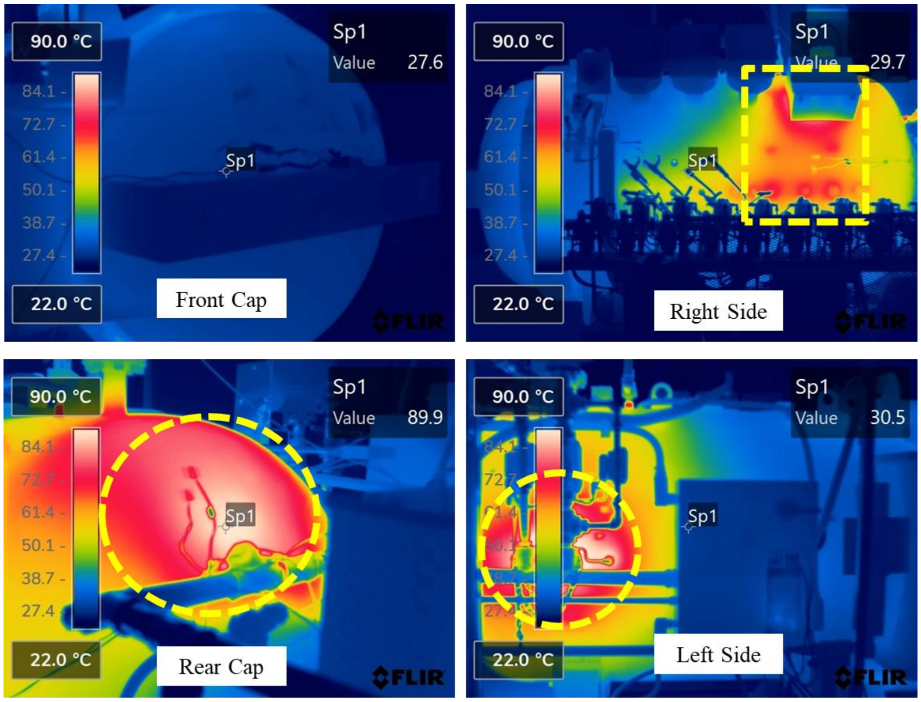


Figure 4 Infrared (IR) thermography of the CRN autoclave during a steady state hold at 180 °C

A total of 21 TCs were deployed. These include 9 outer surface TCs (red), 7 inner surface TCs (yellow), and 5 inner air TCs (blue), as shown in Figure 5. The inside surface and air TCs are connected to the autoclave, while the outside surface TCs are connected to a National Instrument's data acquisition module. All the TCs are set to read values at 1 Hz.

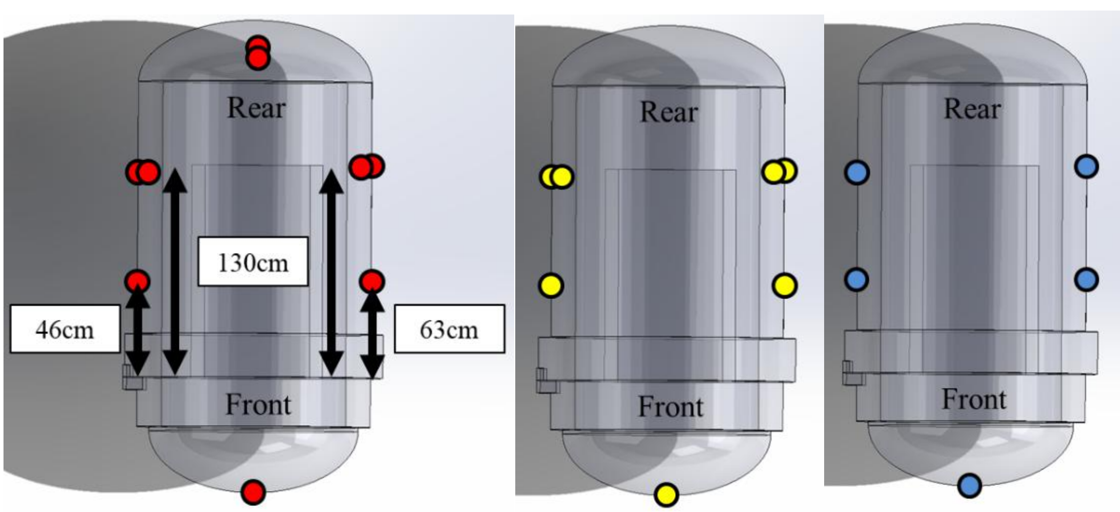


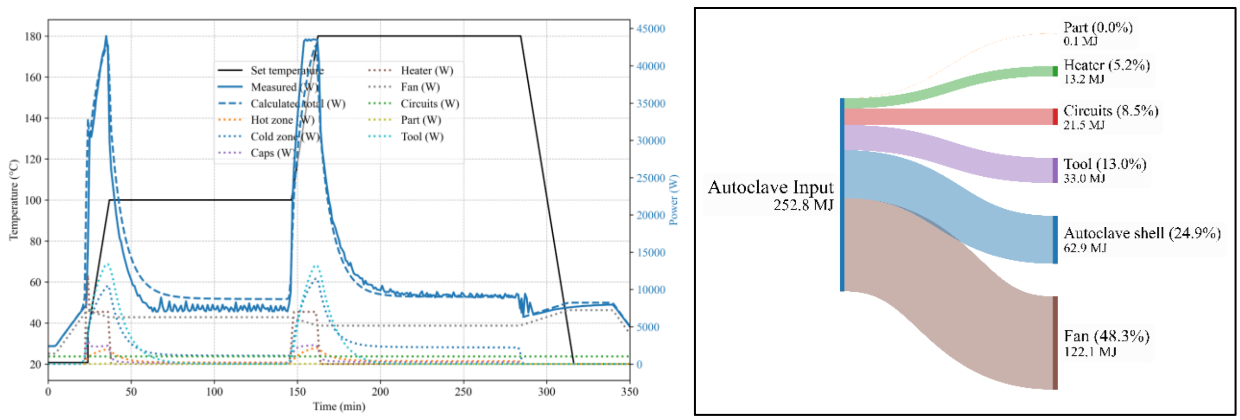
Figure 5. Thermocouples layout for monitoring the CRN autoclave's thermal profile (Red: A/C shell outer surface temperatures; Yellow: A/C shell inner surface temperatures; Blue: A/C inner air temperatures)

3.3. Process

The prepreg samples were laid on the Invar tool via hand layup and sealed using a vacuum bag. Initially, the autoclave pressure increased from 0 to 80 Psig. For the first phase, the temperature is raised to 100 °C at 5 °C/min and held for 2 hours. For the second phase, the temperature increased again to 180 °C at the same ramp rate and held for another 2 hours. Finally, the autoclave is allowed to cool to ambient temperature at 10 °C/min before depressurizing.

4. Results

The estimated power demand and the accumulated energy consumption of the two-hold curing cycle are presented in Figure 6. The results demonstrated a strong agreement between the calculated power demand and the experimental measurements across both the heating and holding stages. In this experiment, the dominant energy consumer was the circulation fan system, which accounted for nearly 48% of the total energy. Between the autoclave shell (25%), the tool (13%), and the heating unit (5%), almost half of the energy was used to heat the equipment. Lastly, the electrical circuits (8.5%) were the baseline power requirement. Since only 0.6 kg of prepreg was cured in this experiment, the energy input to the composite part was negligible.



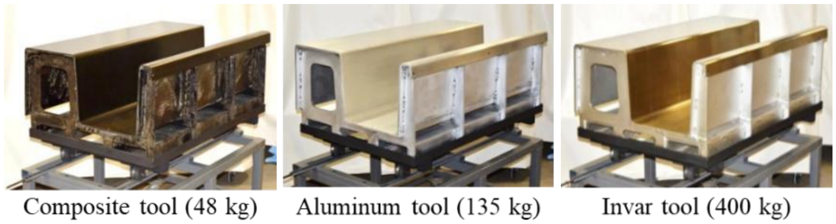
(a) (b)

Figure 6 (a) Comparison of measured and calculated instantaneous power demand of a two-hold curing cycle; (b) Sankey diagram of the cumulative energy distribution in the CRN autoclave.

However, the observed energy distribution does not reflect the maximum energy efficiency of the CRN autoclave, as it was operated at a fraction of its capacity. To determine the theoretical efficiency limits, a parametric study was also conducted, comparing fully loaded autoclaves with different tooling options.

The simulated parametric study considers a load of 8.5 kg of HEXCEL-8552-AGP193-PW, cured on three tools made of different materials: composite, aluminum, and Invar, all with the same dimensions (Figure 7). In practice, cure cycles are often tailored to the thermal lag of the chosen tooling material, and the developed framework can easily accommodate this by updating the input cure cycle parameters. However, for this parametric study, a standardized cycle was intentionally maintained to provide a direct comparison among the three most common tooling materials.

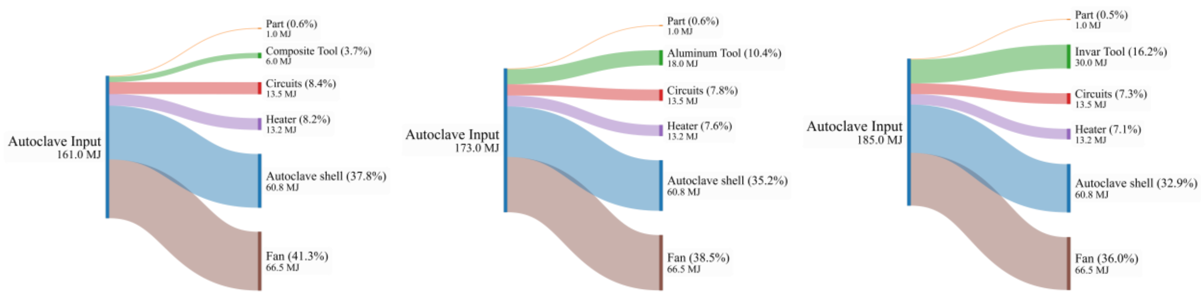
Therefore, the curing cycle followed a standard 3 °C/min ramp rate at 80 Psig, followed by a 2-hour hold, then cooling to ambient temperature.



a. b. c.

Figure 7 Images of the three tooling options evaluated in the parametric study: (a) Composite tool (48 kg); (b) Aluminum tool (135 kg); (c) Invar tool (400 kg).

Even when the autoclave was operated at its maximum capacity, the resulting efficiency remained low (0.5 – 0.6%) (Figure 8). This performance was reflected in the energy intensities of these configurations (Table 2), which varied from 19 to 22 MJ/kg of cured composites. However, these results align with the established benchmarks for research-scale autoclaves that typically report an intensity of 22 MJ/kg [5,6,7].



a. b. c.

Figure 8 Comparative Sankey diagrams for a fully loaded autoclave (8.5 kg part capacity) with three different tooling materials: (a) Composite tool (48 kg); (b) Aluminum tool (135 kg); (c) Invar tool (400 kg).

In this parametric study, the composite tool consumed five times less energy than the Invar tool. However, the two dominant energy consumers were once again (a) the circulation system, which accounted for approximately 40% of the total, and (b) parasitic thermal, which is the heating of the equipment - the tools, the heater, and the autoclave shell, approximately 40-45% of the total.

Table 2 Summary of the parametric study results for the maximum part load (8.5 kg) across different tooling materials, including total energy consumption per run, the resulting CFRP energy intensity and efficiency.

Material	Part Mass (kg)	Tool Material	Tool Mass (kg)	Energy per Run (MJ)	Energy Intensity (MJ/kg)	Energy Efficiency
HEXCEL-8552-AGP193-PW	**8.5**	Aluminum	135	173	21	0.6%
		Invar	400	185	22	0.5%
		Composite	48	161	19	0.6%

5. Conclusion

This paper introduced a comprehensive framework to analyze autoclave energy consumption and efficiency. An autoclave consists of many components, which can be categorized into thermal, mechanical, and electrical subsystems based on their functionality. By characterizing the autoclave as an integrated assembly of interdependent subsystems, the model accounts for the dynamic power demands of these components throughout the entire curing cycle. A two-hold case study was conducted to validate the framework, and a parametric study was performed to determine the theoretical efficiency limits of the CRN autoclave.

This system-level approach is particularly critical given that the initial investment and operational cost for industrial autoclaves are highly sensitive to size and specification. Because the margin for error is small and the financial risk is high, a digital autoclave system description is necessary to transition from traditional 'trial-and-error' methods toward a more predictive, systematic framework.

6. References

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