

Summary of Thermoforming Analysis

The environmental analysis is made up two components 1) energy used to create the thermoformed shell, 2) emissions as a result of the process.

The energy used to create n thermoformed shells can be found by the following equation:

$$\text{Energy} = [3 + (n * 1.007) + (n * 17.26)] \text{ MJ} \quad (\text{f1})$$

The formula takes into account that approximately 1min 30 secs is used to fixture and defixture a part/shell. This formula should be used whenever a group is thermoforming a new batch of shells.

The energy used while the machine is idling between cycles is determined by:

$$\text{Idle Energy} = [n * 0.18] \text{ MJ} \quad (\text{f2})$$

This formula is to determine the energy used for any extra time on the thermoforming machine aside from that which is accounted by equation (f1).

Emissions from the process are assumed to be CO₂, SO₂ and NO_x

CO₂ emissions for n thermoformed shells:

$$\{n * 1.86 + [3 + (n * 1.007) + (n * 17.26)] * 0.186\} \text{ kg} \quad (\text{f3})$$

SO₂ emissions for n thermoformed shells:

$$\{[3 + (n * 1.007) + (n * 17.26)] * 7.63 * 10^{-4}\} \text{ kg} \quad (\text{f4})$$

NO_x emissions for n thermoformed shells:

$$\{[3 + (n * 1.007) + (n * 17.26)] * 3.75 * 10^{-4}\} \text{ kg} \quad (\text{f5})$$

Practical Procedure

- 1) Keep track of the number of thermoformed shells created
- 2) Keep track of the total time, and back calculate the idle time between cycles
- 3) Apply formulas(f1-f5) to calculate the environmental impact

Measurements

Measured Power Properties

Process	Power	Time
Warm Up	10kW	4 min 43 sec \approx 5 min
Idle	3kW	
Operating (Heater)	3kW	3 min 30 sec

Breakdown of Operating Time

Heater: 2 min 20 sec

Vacuum: 40 sec (assumption)

Fan: 30 sec (assumption)

Duty Cycle: idle time : operating time 45 sec: fixturing(assumption)
 1 min 30 sec : 3 min 30 sec 45 sec: defixturing (assumption)

Plastic Properties

Type of thermoplastic: *Acrylonitrile Butadiene Styrene (ABS)*

Density of thermoplastic: $1010 - 1210 \text{ kg/m}^3$

Volume of thermoplastic: $23'' \times 18'' \times 0.0625'' = 25.875 \text{ in}^3 = 0.424 * 10^{-3} \text{ m}^3$

Weight of Plastic: $1210 * 0.424 * 10^{-3} = 0.513 \text{ kg}$

Primary Energy required for thermoplastic manufacture: $91 - 102 \text{ MJ/kg}^i$

Electrical Grid energy used for single piece of plastic): $0.33 * 0.513 * 102 = 17.26 \text{ MJ}$

CO₂ emission from manufacture of thermoplastic: $3.27 - 3.62 \text{ kg/kg of thermoplastic}$

CO₂ emission from a single shell: $3.62 * 0.513 = 1.86 \text{ kg}$

Venturi Vacuum Pump and Air Compressor Properties

Time to evacuate the mold = 2 secs (assumption)

Volume of Mold: $18'' \times 14'' \times 8'' = 2016 \text{ in}^3 = 1.1666 \text{ ft}^3$ (overestimate)

Flow rate of air out of the mold: $\frac{1.1666}{2} * 60 = 35 \text{ cfm}$

Pressure of the vacuum to hold the mold: $28.5'' \text{ Hg} = 13.9 \text{ psi}$ (assumption)ⁱⁱ

Pressure difference between mold and surroundings: $14.7 - 13.9 = 0.8 \text{ psi}$

Pressure drop at the point of evacuating the mold: 3 psi (observed/assumption)

Key Assumptionsⁱⁱⁱ:

- 1) air compressors deliver 4-5 cfm per hp at 100 psi
- 2) every 2 psi of pressure increases or decreases the power draw of a compressor by 1 %.

Assume air compressor UP6-20-135 (20hp, 83 cfm @ max psi, 125 max psi)^{iv}

Air compressor provides 4.15cfm per hp at 125 psi

For 35 cfm, compressor utilizes $8.43 \approx 8.5 \text{ hp}$ at 125 psi

At 3 psi, 61% reduction in hp, energy used: 3.3 hp (2.46 kW)

At 1 psi, 62% reduction in hp, energy used: 3.23 hp (2.40 kW)

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The difference in power consumption is small, the higher power consumption will be used to calculate the energy consumption of the air compressor and venturi pump system.

Fan Properties

Power used by fan: 300W (assumption)

Energy Model Calculations

Process Energy (Single Cycle)

Process	Power	Time	Energy
Warm Up	10kW	4 min 43 sec \approx 5 min	3MJ
Operating (Heater)	3kW	3 min 30 sec	0.63MJ
Operating (Vacuum)	2.46kW	40 sec	0.098MJ
Operating (Fan)	300W	30 sec	0.009MJ
Idle	3kW	1 min 30 sec	0.27MJ
Total			4.007MJ

Material Energy used for 1 single thermoformed shell: 17.26MJ

Total Electrical Grid Energy for 1 single thermoformed shell: 21.26MJ

Energy Usage for n thermoformed shell:

$$[3 + (n * 1.007) + (n * 17.26)] \text{ MJ}$$

Energy Usage for n idle mins (idle time between 2parts):

$$[n * 0.18] \text{ MJ}$$

Energy required to warm up the thermoforming machine should always be included into the environmental accounting even if the thermoforming equipment is switched on, and whenever there is a break in the thermoforming of batches of shells.

Emissions

CO₂ emissions for n thermoformed shell:

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SO₂ emissions for n thermoformed shell:

$$\{[3 + (n * 1.007) + (n * 17.26)] * 7.63 * 10^{-4}\} \text{ kg}$$

NO_x emissions for n thermoformed shell :

$$\{[3 + (n * 1.007) + (n * 17.26)] * 3.75 * 10^{-4}\} \text{ kg}$$

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ⁱ <http://www.grantadesign.com/solutions/education/ABS.htm>

ⁱⁱ <http://plastics.turkavkaz.ru/processes/thermoforming/parametres.htm>

ⁱⁱⁱ <http://www.maintenanceresources.com/ReferenceLibrary/AirCompressors/kaeserpage8.htm>

^{iv} <http://air.irco.com/IS/modelComp.asp/item/12771>