ILF/18/093:

Prediction and Control of Humidity of Glove Formers in Vulcanization Ovens

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Project Details

Project Objectives:

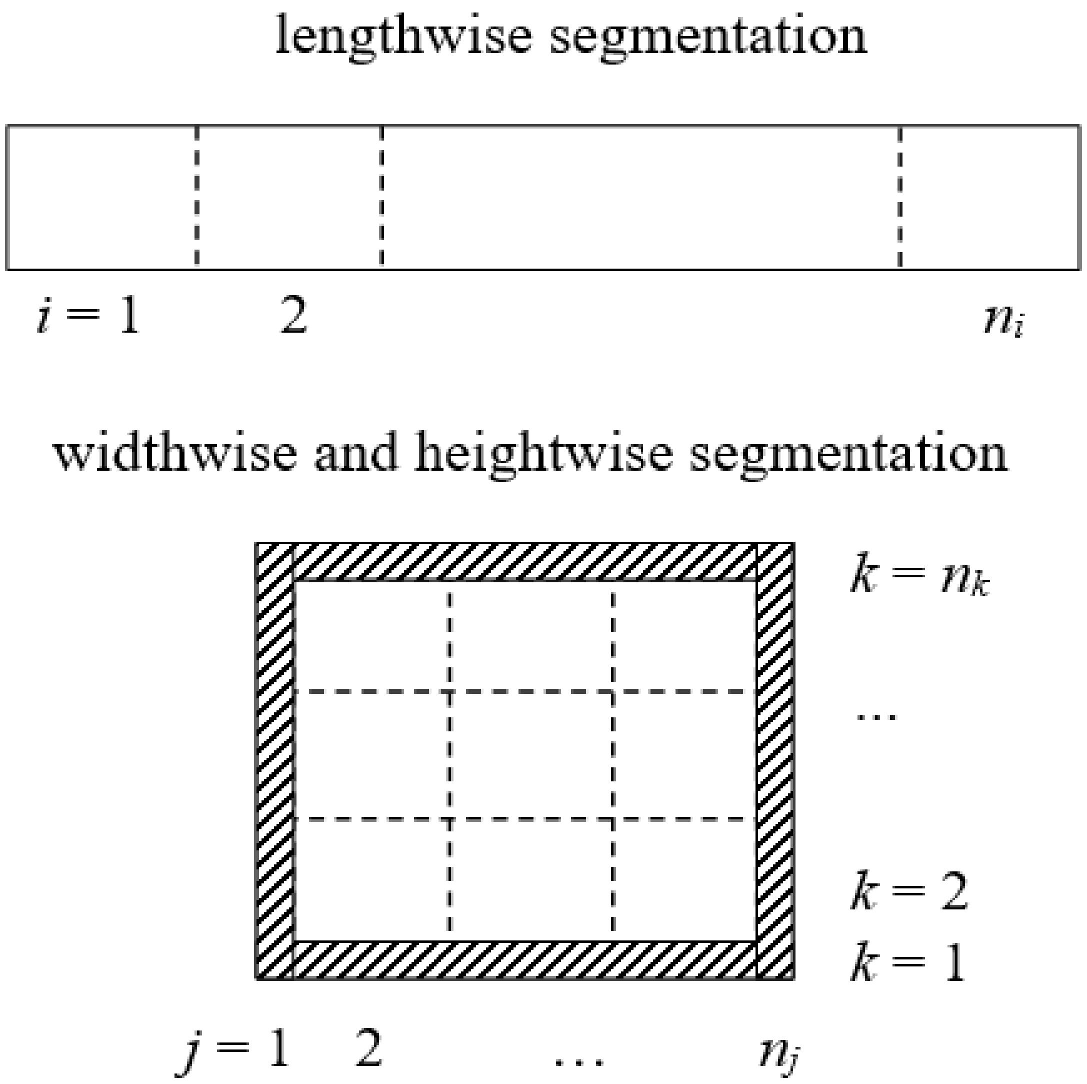
- **To predict the humidity of glove formers in a vulcanization oven using thermodynamics.**
- **To propose efficient control of the humidity of glove formers exiting a vulcanization oven.**

Derivation of temperature profile of oven

Why is this important?

- In the processing of gloves, an important stage is the drying of gloves in the vulcanization oven.
- The moisture content of the latex film on the formers will affect the quality of the gloves and the subsequent stages in the processing. If the humidity is too high, the gloves are too wet for packaging.
- However, if the humidity is too low, the gloves tear more easily during stripping of the gloves from the formers resulting in higher percentage of defects.
- To predict the humidity of glove formers, the first step is to develop temperature profiling of oven.

Segmentation of oven



lengthwise segmentation

widthwise and heightwise segmentation

Modelling of heat transfers

- Heat transfers between zones were determined as follows:

  Solid to solid: Conduction

  Solid to fluid: Convection and radiation

  Fluid to fluid: Convection

- Conduction and convection can be described using

$$\dot{Q} = \frac{T_a - T_b}{R}$$

- For conduction:

$$R = \frac{\text{length}}{\text{thermal conductivity} \times \text{area}}$$

- For convection:

$$R = \frac{1}{\text{heat transfer coefficient} \times \text{area}}$$

- For radiation: $\dot{Q} = \varepsilon\sigma A(T_a^4 - T_b^4)$

ε and A are the emissivity and surface area of the radiating body, respectively, and σ is the Stefan-Boltzmann constant (5.67×10^{-8} $\mathrm{Wm^{-2}K^{-4}}$).

- For heat transfer through airflow:

$$P_v = vC_pA\rho(T_a - T_b)$$

C_p is the specific heat capacity of air, A is the area of airflow, ρ is the density of air

- The temperature change is modelled using

$$P = C\frac{dT}{dt}$$

$$C = \text{specific heat capacity} \times \text{volume} \times \text{density}$$

A MATLAB program was developed based on the thermodynamic equations.

User-input parameters:

- Oven length
- Oven width
- Oven height
- Number of zones
- Thickness of insulation
- Power of burners
- Ambient temperature

Other parameters that can be changed with some modifications of the program:

- Number of segments lengthwise (n_i) – must be an integer multiple of the number of zones
- Number of segments widthwise (n_j) – odd number is preferred
- Number of segments heightwise (n_k) – odd number is preferred

The software program can be used to

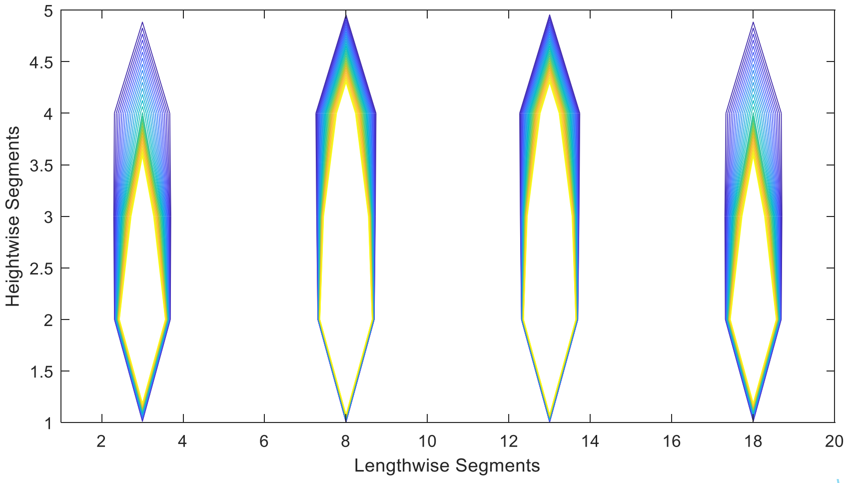
1. Analyse the relative significance of different heat transfer mechanisms.
2. Investigate temperature profile changes due to parameters changes.
3. Compute the amount of water evaporation which can be achieved.
4. Obtain humidity profile incorporating energy absorbed due to evaporation.

Sample results are shown here for the user-input parameters as follows:

- Oven length = 50m
- Oven width = 2m
- Oven height = 2m
- Number of zones = 4
- Thickness of oven walls = 3mm
- Power of burners = the 1st and 4th burners are 20kW each, the 2nd and 3rd at 50kW each
- Ambient temperature = 40°C

Analyse the relative significance of different heat transfer mechanisms.

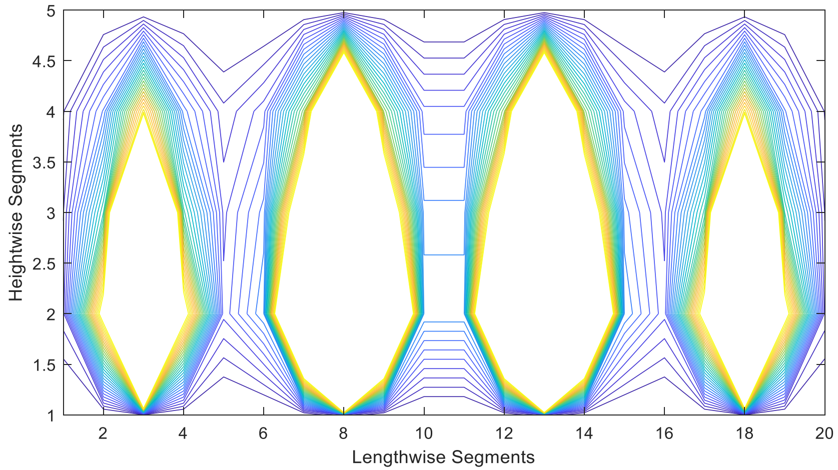
Example: Conductive and convective power losses from each segment

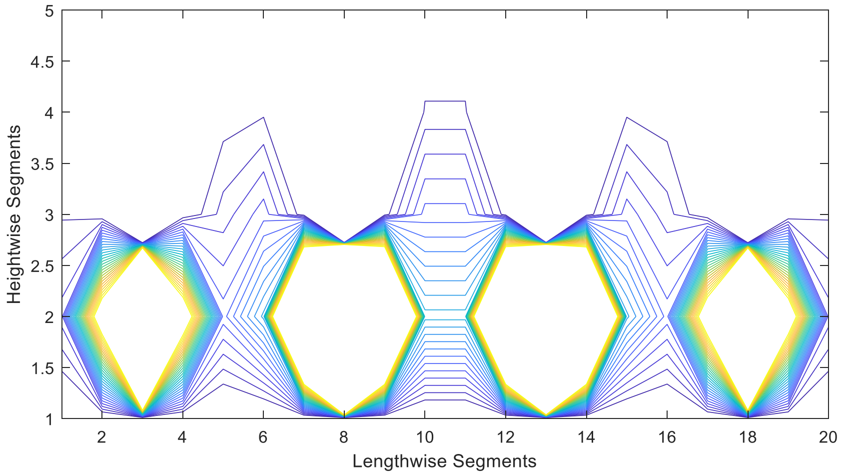


lengthwise

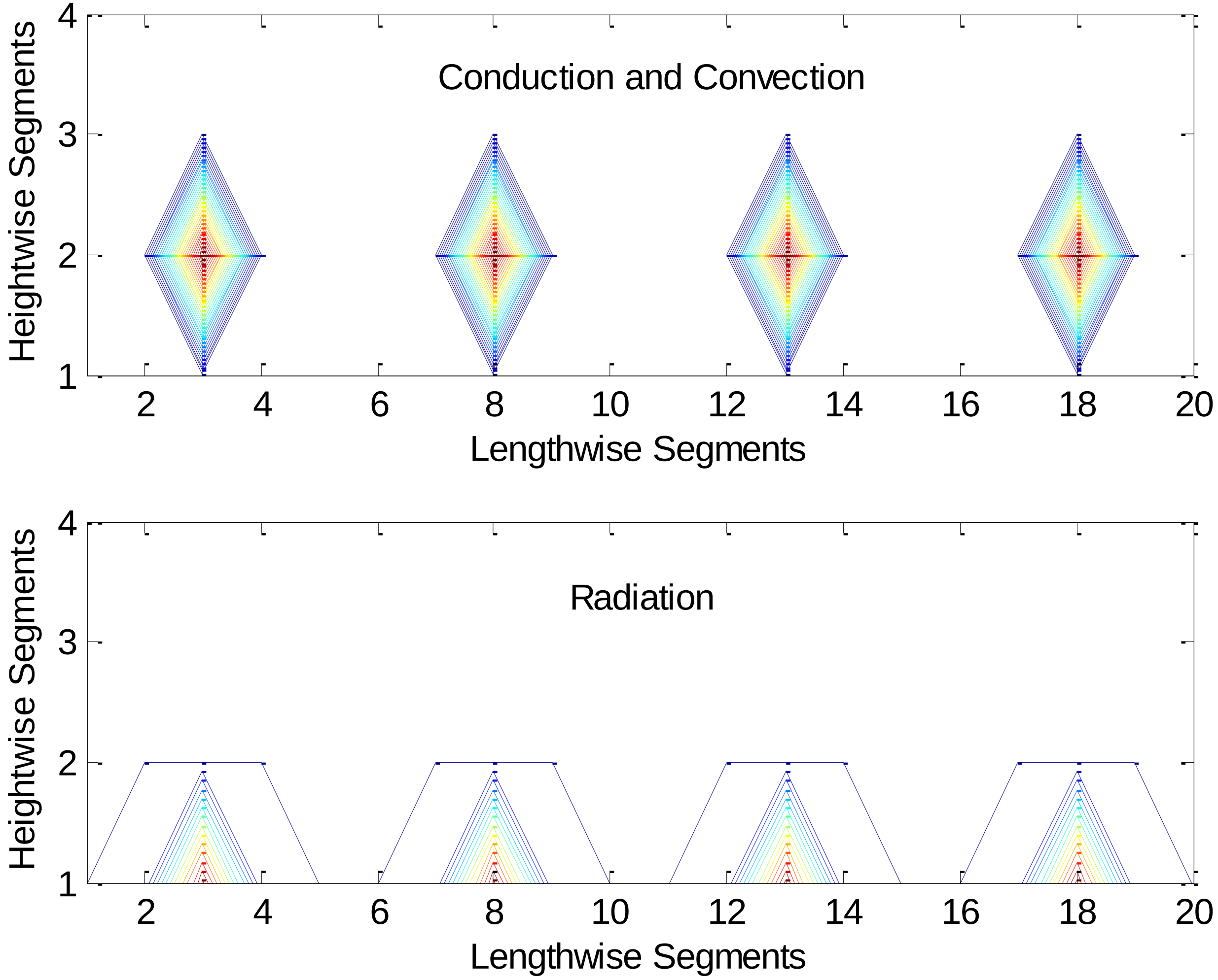
widthwise

heightwise



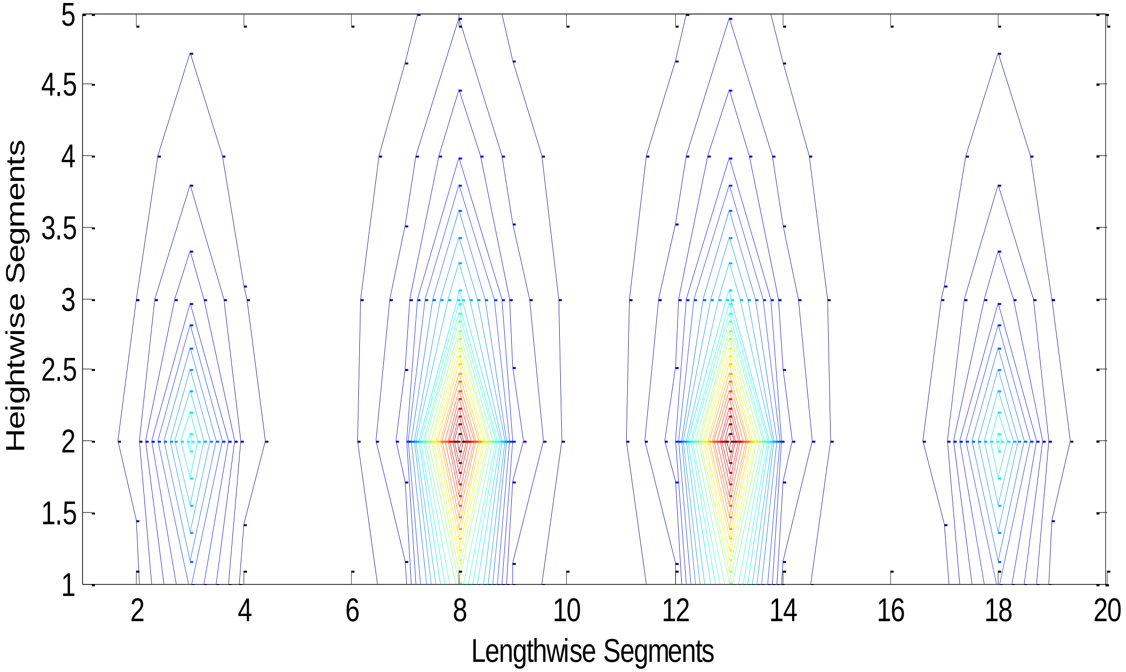


Example: Different types of heat transfers can their main locations can be analyzed

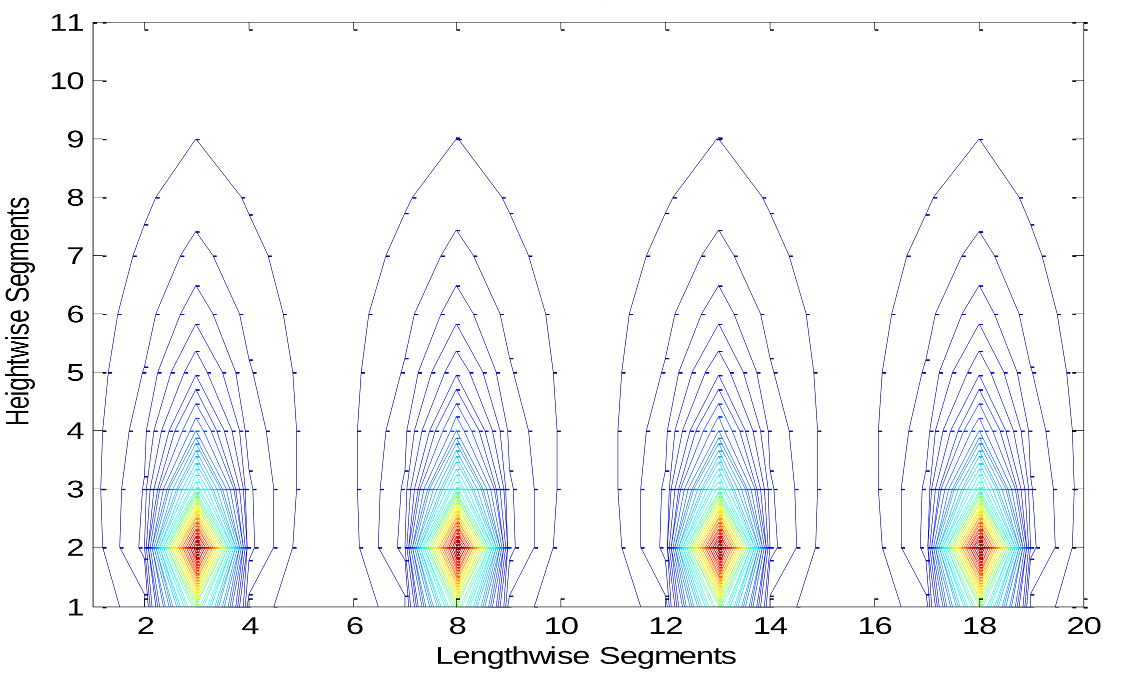


Investigate temperature profile changes due to parameters changes.

Example: Change in power of burners (also change in the number of segments)



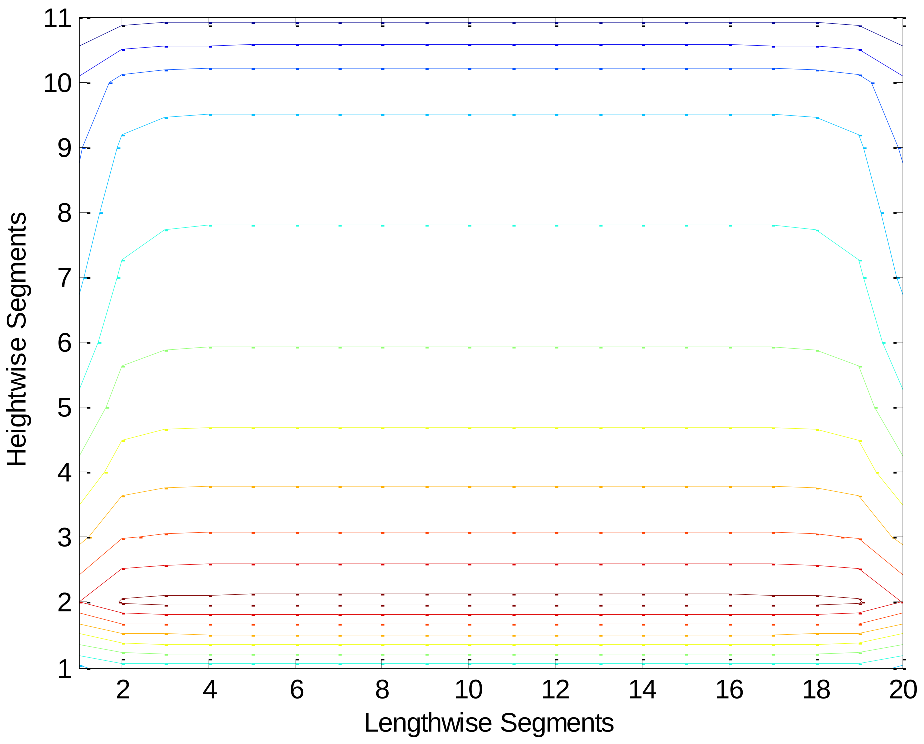
all burners at 30kW



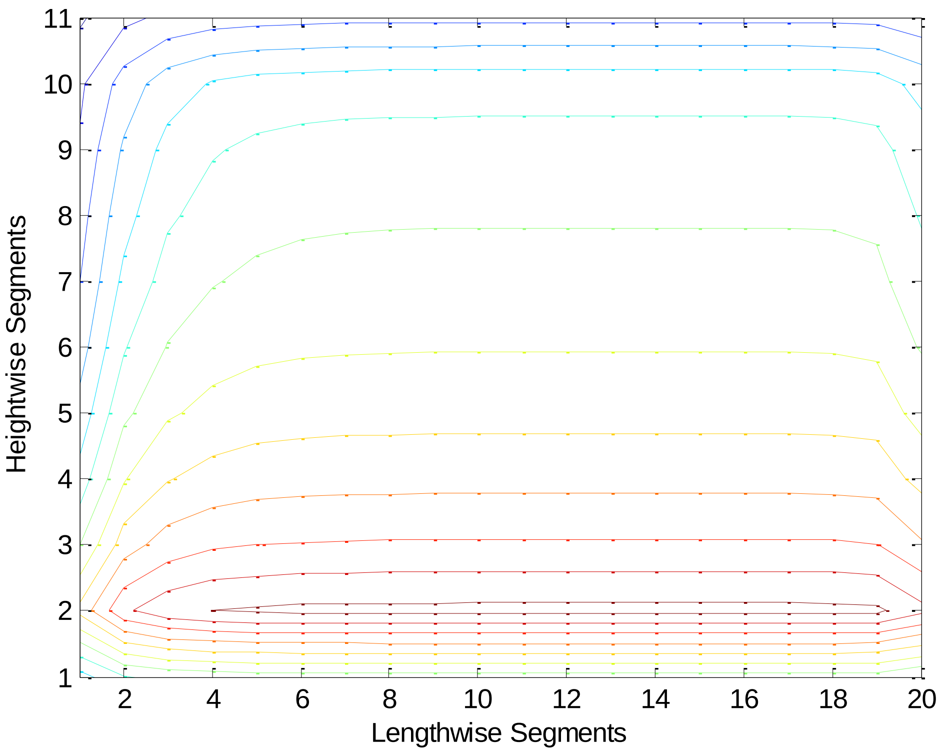
Example:

Change to indirect heating such that hot air from the burners enters through some ducts beneath the oven

no horizontal airflow

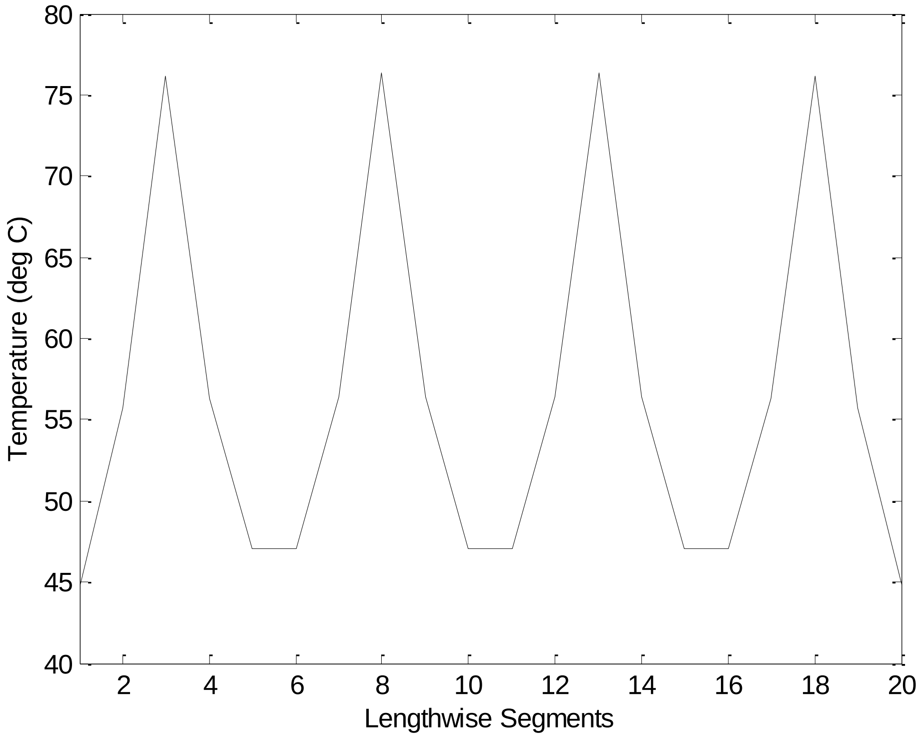


with horizontal airflow



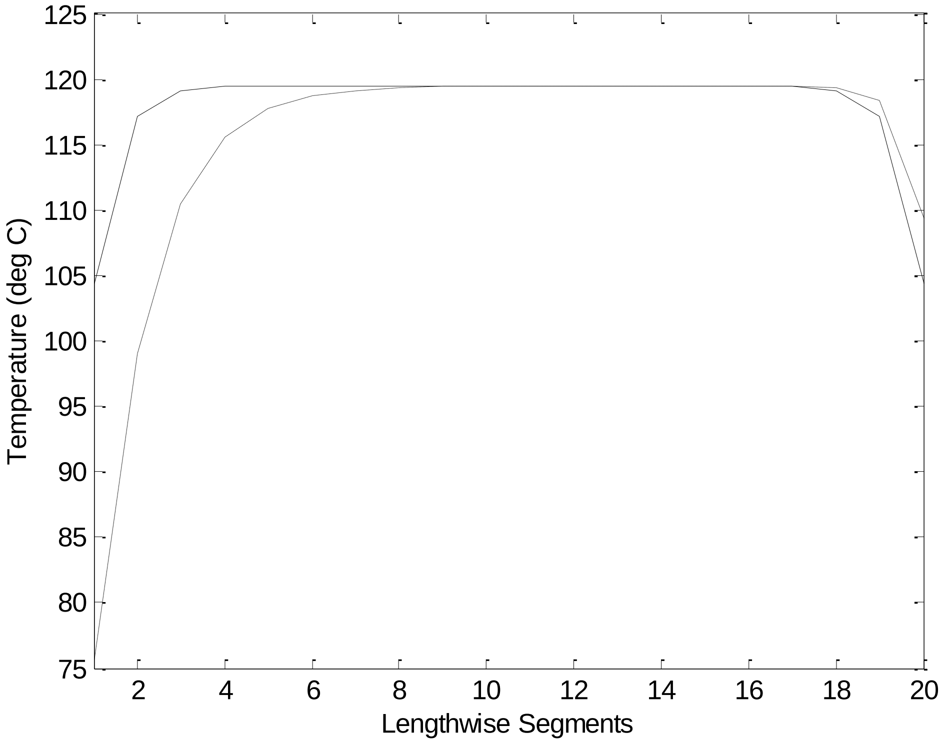
Example: Comparison of direct heating and indirect heating

direct heating



indirect heating

dotted line (horizontal airflow)



Evaporation model based on film properties and conveyor speed

- The process can be described in 3 major stages.
- Stage I – Evaporation of water and particle ordering

  At the beginning of film formation process, the polymer particles are at their most mobile phase due to their characteristic Brownian motion. The water concentration is uniformly distributed throughout the drying latex. The evaporation of water brings the particles close together to form a dense array. This stage is usually characterized by constant evaporation of water, which is equal to the evaporation of free water for an aqueous solution of electrolytes and emulsifiers with the same concentrations. The main driving mechanism is the temperature and vapour pressures of the water surface which is related to the humidity.

- Stage II – Particle deformation

  In the second stage, the particles deform into a polyhedral formation to fill in the void left by the continued water-loss. Continued evaporation leaves voids within the interstitial boundaries of the particles. The transition from Stage I to Stage II is characterised by a significant drop in the evaporation rate of water in the latex.

- Stage III – Coalescence and inter-diffusion

  In third stage, a homogeneous, coherent film is produced by coalescence and inter-diffusion between the polymer particle boundaries. This final stage is usually characterised by a plateau in the weight loss measurements as virtually all the water has evaporated from the latex film.

- An experiment was conducted to measure the value of the drying time constant τ for different film thicknesses.
- The undried latex films were prepared by dry coagulant dipping process.
- Both natural rubber (NR) compound and nitrile rubber (NBR) compound were tested.
- Drying with temperature at 120°C.

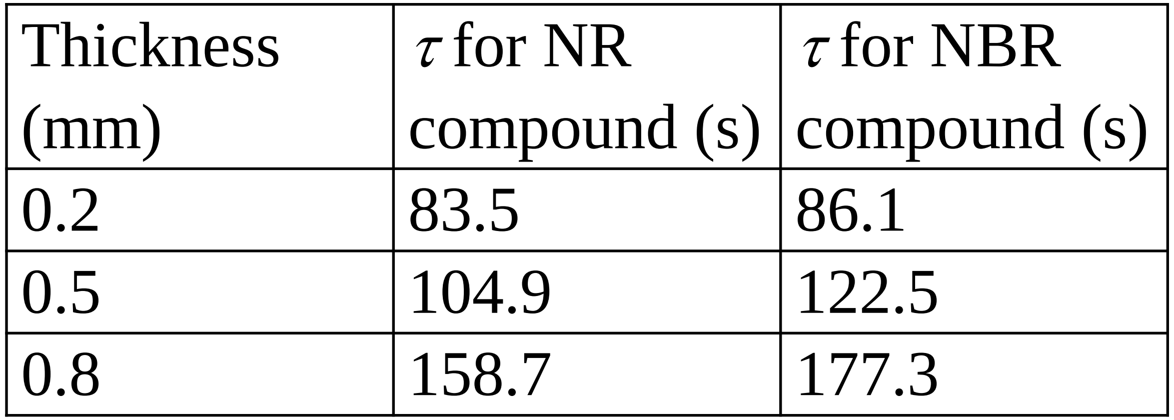
Measurement of latex film thickness using a dial caliper.

$$m = ce^{-t/\tau},$$

$$e^{-t/\tau} = \frac{m}{c},$$

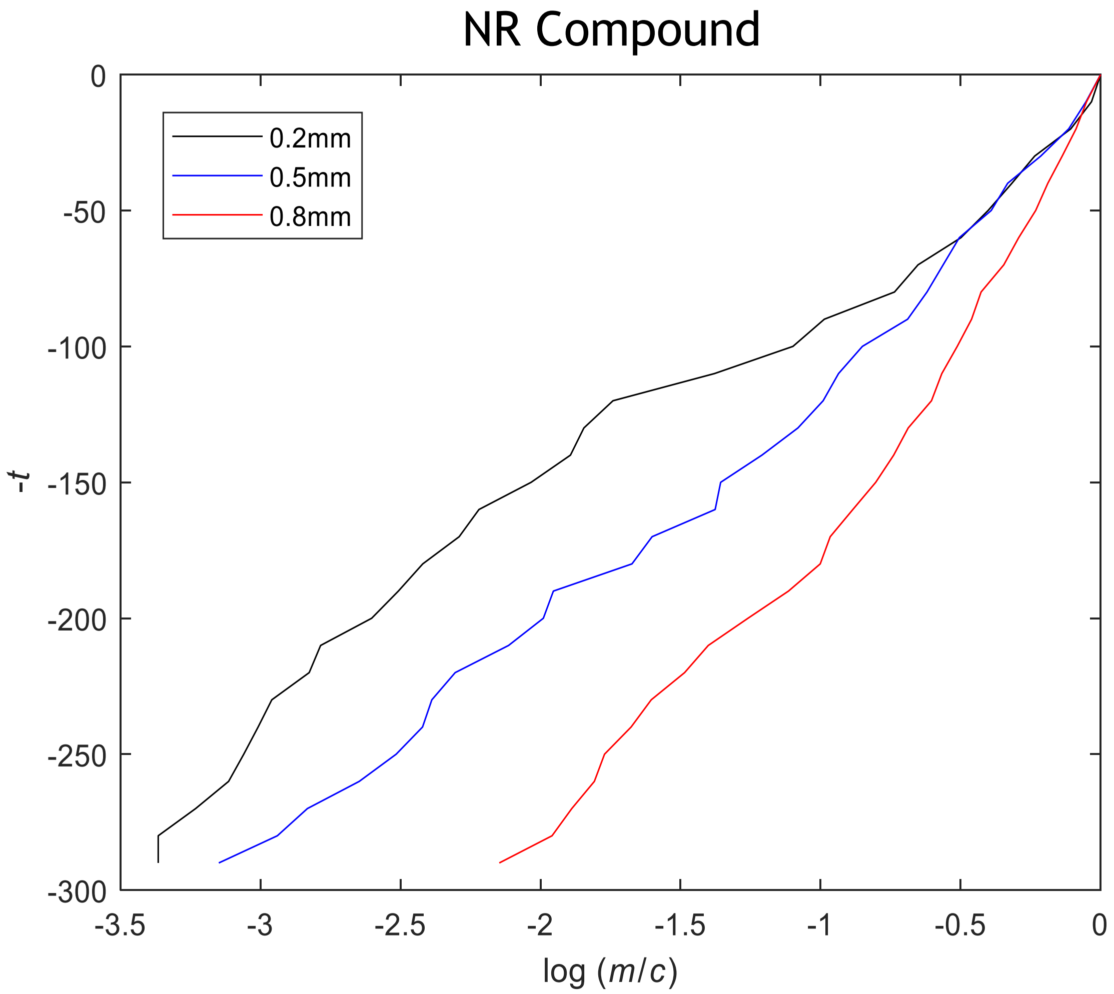
$$-\frac{t}{\tau} = \log\left(\frac{m}{c}\right),$$

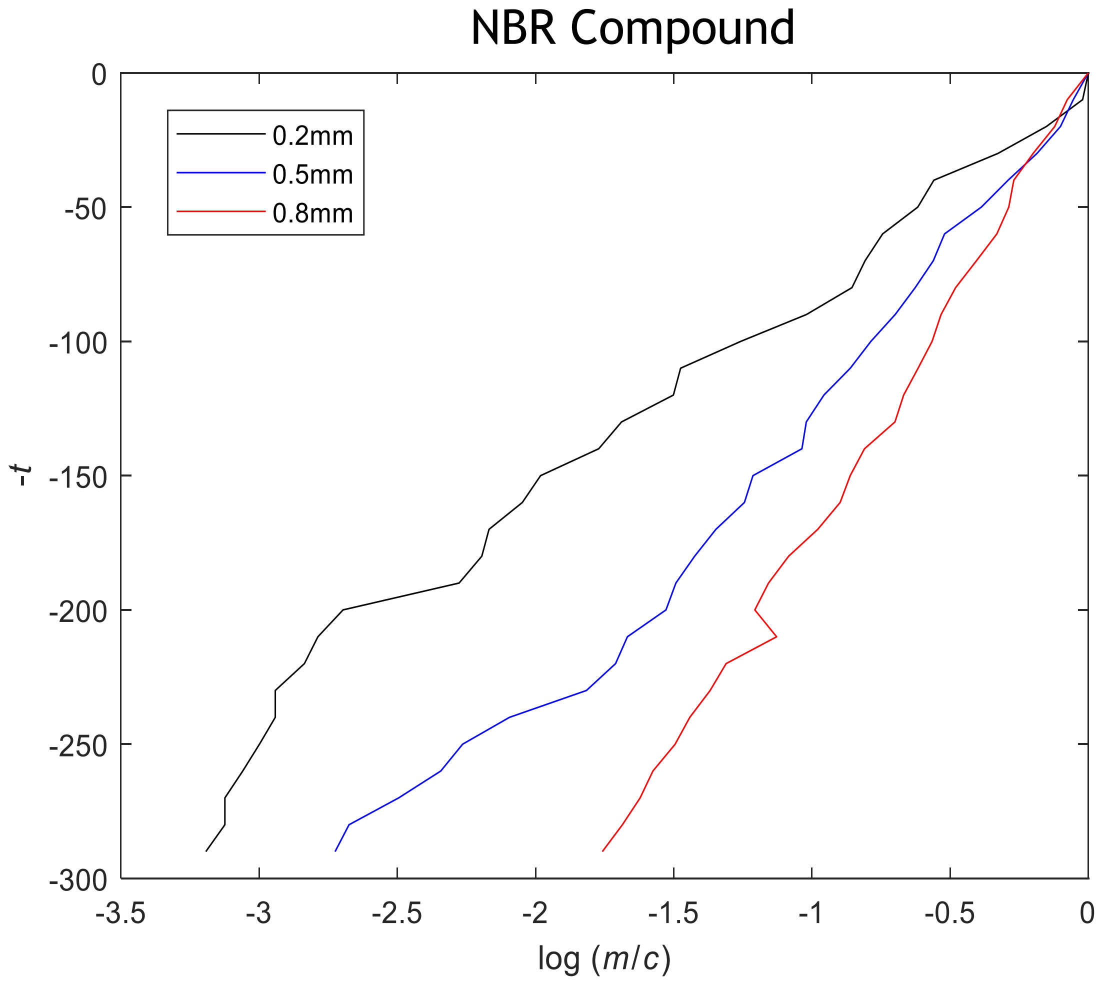
$$-t = \tau \log\left(\frac{m}{c}\right)$$



Thickness (mm)	τ for NR compound (s)	τ for NBR compound (s)
0.2	83.5	86.1
0.5	104.9	122.5
0.8	158.7	177.3

m represents the mass and *c* is the initial mass


NR Compound


NBR Compound

- For the verification of humidity, an experiment was carried out in the laboratory to measure the amount of water evaporated after drying for 10 minutes in the oven at 120°C.

Thickness (mm)	Type	Measured (g)	Fitted using evaporation curve (g)
0.2	NR	1.62	1.95
0.2	NBR	1.36	1.73
0.5	NR	4.01	4.89
0.5	NBR	3.52	4.36
0.8	NR	6.61	7.64
0.8	NBR	5.55	6.73

- The accuracy is higher for thicker gloves.
- The main source of error is that the decay in evaporation is not exactly exponential, although it has been modeled as such.
- For thicker gloves, there is greater time duration where the drying is in Stage I, leading to more accurate results.

Derivation of humidity profile of oven

- For the majority of the time the former is in the oven, the film formation is in Stage I. Water evaporates at a constant rate close to that of an electrolyte water solution. The amount of water (in kg) evaporated per second is given by

$$m_w = (25 + 19v)A_f\left(\frac{X_s - X}{3600}\right)$$

v is the airflow rate (velocity of air)

X_s is the maximum humidity of saturated air at the same temperature at the surface (kg H_2O in kg dry air)

X is the humidity ratio of air (kg H_2O in kg dry air)

A_f is the surface of the former taken as 0.04m^2

- The value of X_s is calculated from

$$X_s = \frac{V_D}{D}$$

V_D is the saturated vapour density in kg/m^3 and D is the density of dry air in kg/m^3 in atmospheric pressure

$$V_D = \frac{5.018 + 0.32321T + 8.1847\times10^{-3}T^2 + 3.1243\times10^{-4}T^3}{1000}$$

$$D = \frac{\text{pressure}}{\text{specific gas constant for dry air} \times (T + 273.15)}$$

- The value of *X* can be calculated from

$$X = \frac{\mathrm{RH} \times X_S}{100}$$

- As water is evaporated, there are less and less molecules of water at the surface of the former available for evaporation (Stages II and III). This effect is modeled by an additional multiplicative factor comprised of an exponential decay. The amount of water (in kg) evaporated per second is adjusted to

$$m_w = (25 + 19v) A_f \left(\frac{X_s - X}{3600} \right) e^{-t/\tau}$$

- The power absorbed due to evaporation needs to be computed.
- The amount of water (in kg) evaporated per second, m_w, is used to calculate the amount of power needed for the evaporation, where

$$P_{eva} = H_v N_g m_w$$

H_v is the enthalpy of vaporisation of water

N_g is the number of gloves in a particular segment

- The total power gain *P* in a segment in the oven is given by

$$P = P_b + P_v - P_c - P_r - P_{eva}$$

P_b is the power gain due to the burners

P_v is the power gain due to airflow

P_c is the power loss due to conduction and convection

P_r is the power loss due to radiation

P_{eva} is the power absorbed due to the evaporation

Prediction of humidity of glove formers exiting oven

- In the software program, the equation for the computation of humidity is

$$\mathrm{RH} = \frac{\text{partial pressure of water vapour}}{\text{equilibrium vapour pressure of water}} \times 100$$

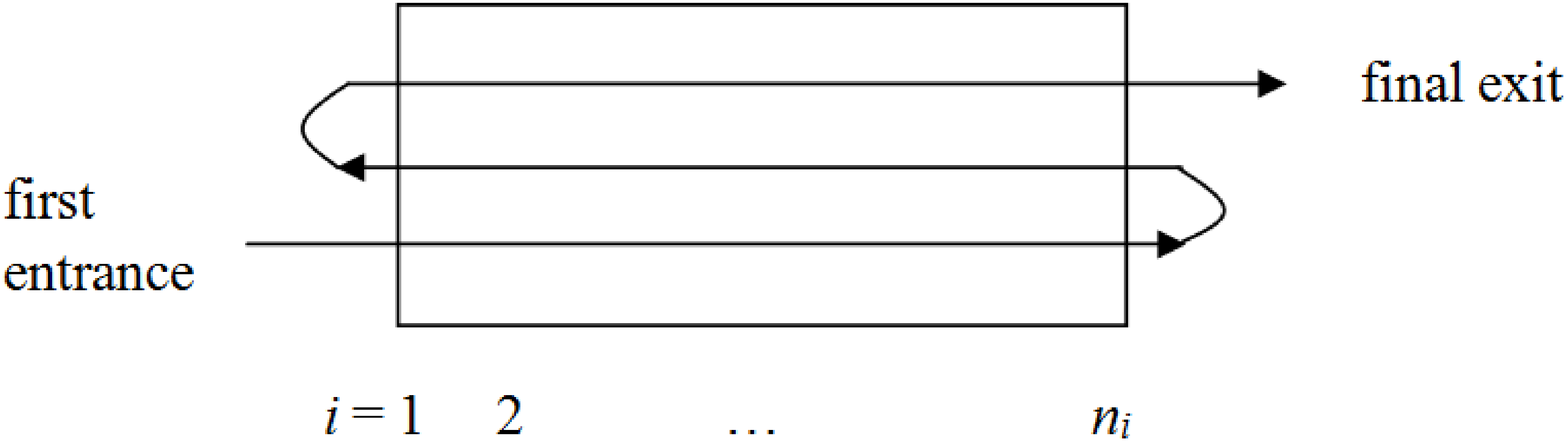
$$\mathrm{RH} = \frac{(X + (m_w / \text{mass of air}))}{X_s} \times 100$$

The humidity in the oven can be treated in three different ways:

- Set as a constant; this assumes that there is a system installed to extract the moisture from air so that the humidity will stay at a predefined level.
- Computed based on the assumption that the air in some segments specified by the user will be recirculated air with a predefined humidity.
- Computed without any system for moisture extraction; this means that the humidity will eventually increase to 100% due to the evaporation adding to the moisture content of air.

Results are shown for the following user-input parameters:

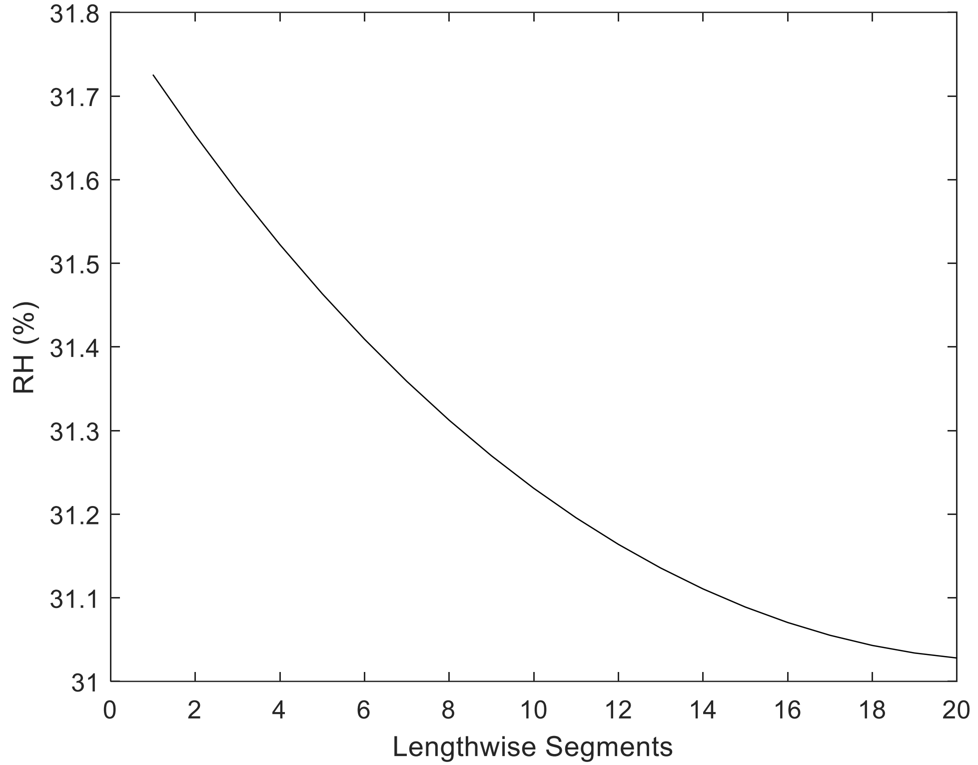
- Oven length = 50m
- Oven width = 2m
- Oven height = 2m
- Thickness of oven insulation = 0.1m
- Number of zones = 4
- Power of burners = 30kW each
- Ambient temperature = 40°C
- Number of layers = 3
- Number of gloves per segment = 10
- Line speed = $0.25 ms^{-1}$
- Airflow rate = $0.1 ms^{-1}$ upwards only
- Drying time constant, τ = 182s



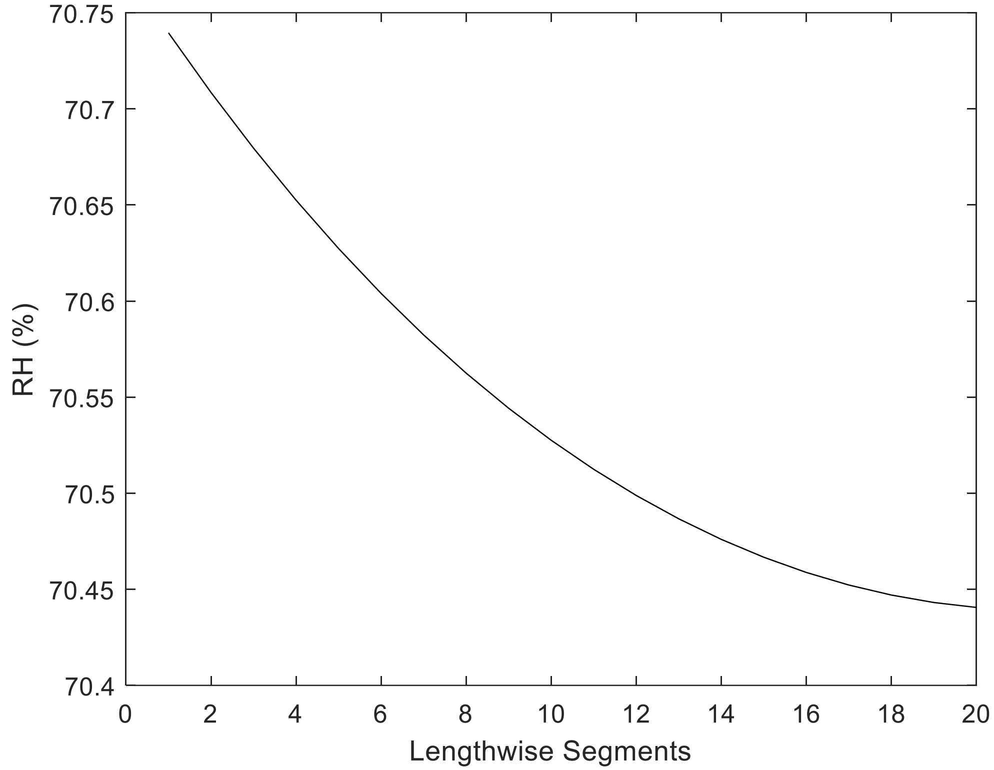
Three-layer arrangement of conveyors

Humidity profile lengthwise across the oven with recirculation

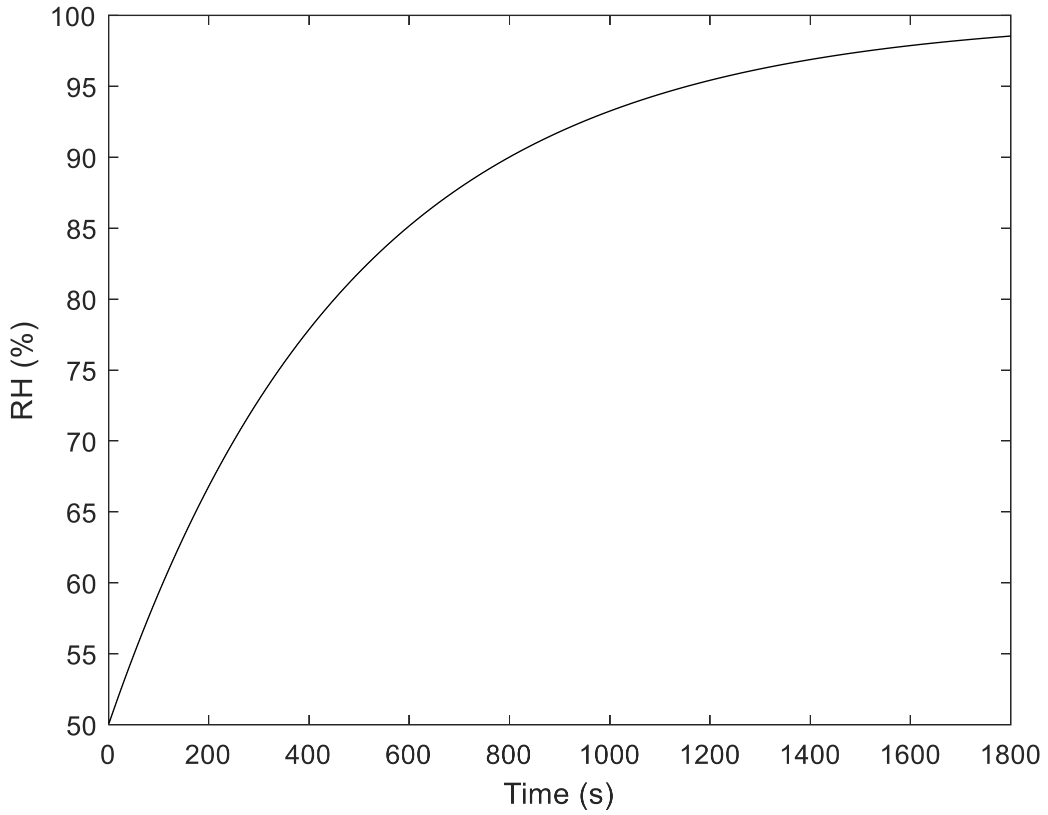
air humidity of 30%



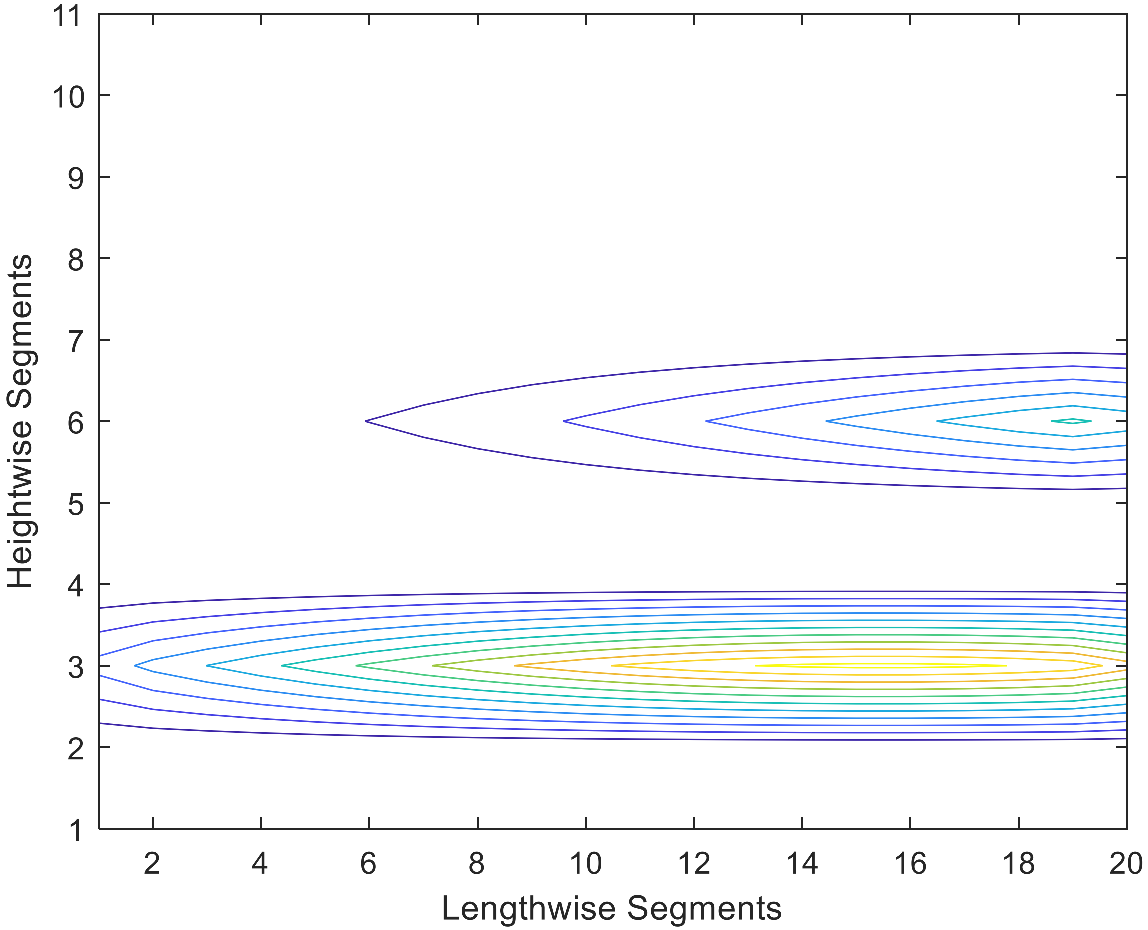
air humidity of 70%



Evolution of mean humidity in the oven in the case where there is no system for moisture extraction.



Profile of power loss due to evaporation



- The amount of water (in kg) is determined using

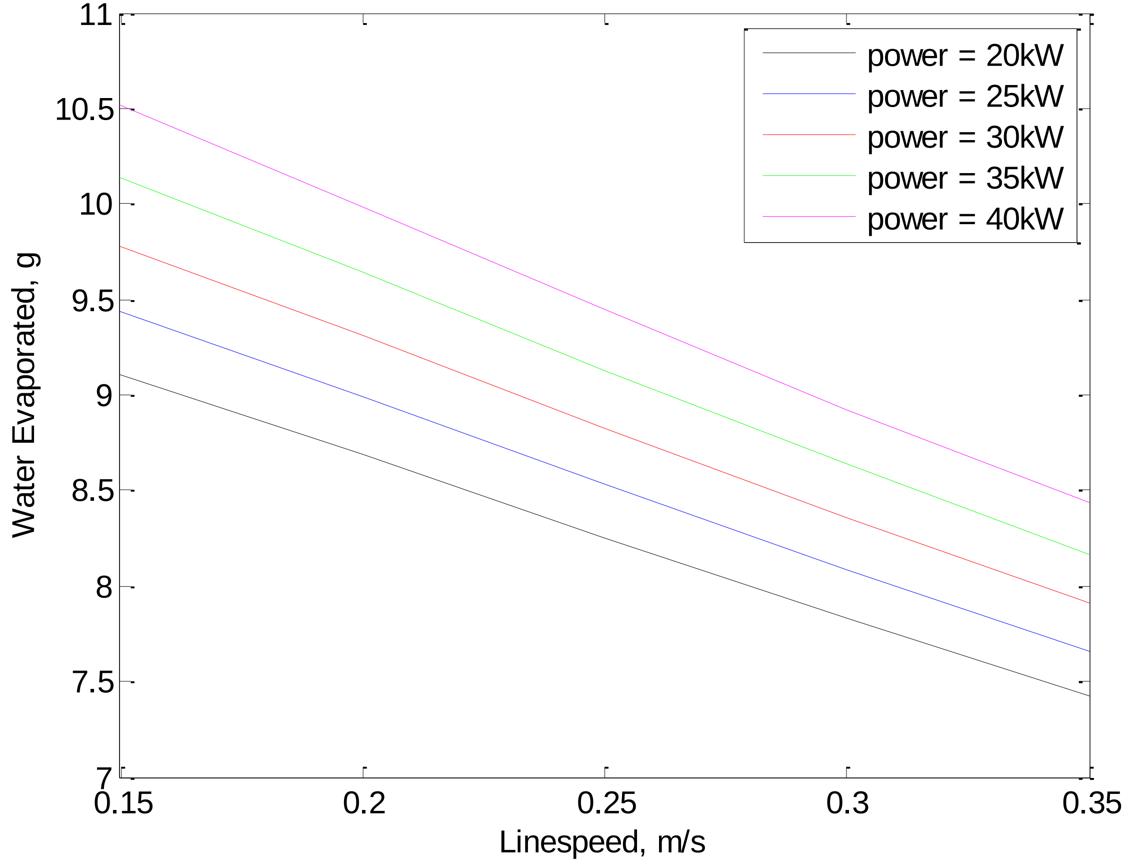
$$e_w = \frac{\text{average}(m_w) \times L \times N_L}{N_g \times S}$$

where average(m_w) is the average amount of evaporation per second for segments containing glove formers, L is the length of the oven, N_L is the number of layers in the oven, N_g is the number of gloves in a segment and S is the line speed in ms^{-1}.

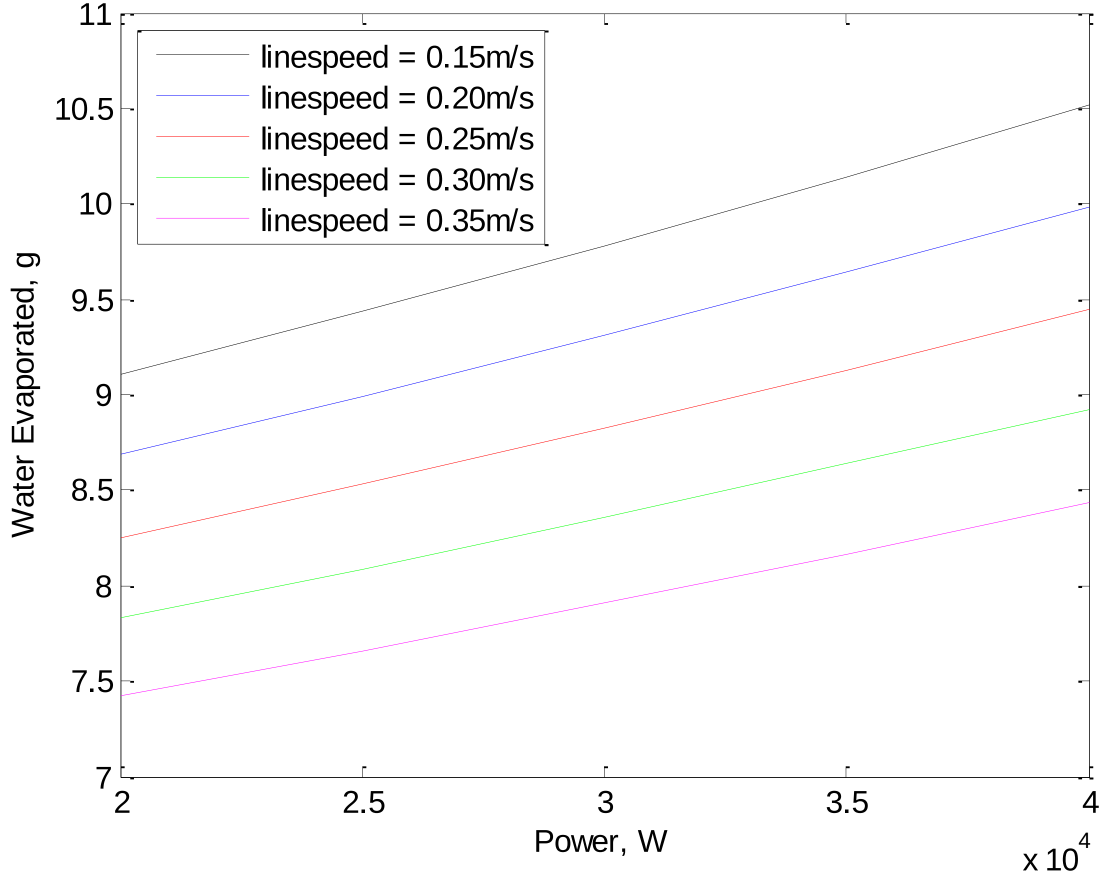
- The moisture content of the glove formers exiting the oven can be computed if the initial moisture content is known. The relationship is

final moisture content =
initial moisture content – amount evaporated

Water evaporated versus linespeed



Water evaporated versus burner power



Effects of specification changes on energy consumption and target achievement

User-input parameters:

- Oven length = 50m
- Oven width = 2m
- Oven height = 2m
- Thickness of oven insulation = 0.1m
- Number of zones = 4
- Ambient temperature = 50°C
- Number of layers = 3
- Number of gloves per segment = 10
- Airflow rate = 0.1ms^{-1} upwards only
- Drying time constant, τ = 125s
- Humidity assumption: recirculated air with a humidity of 60%
- Target amount of water evaporated per glove = 6g

Power of burner (kW)					Temperature at centre of zone (°C)			
Zone 1	Zone 2	Zone 3	Zone 4	Total	Zone 1	Zone 2	Zone 3	Zone 4
40	40	30	30	140	84.98	88.26	86.01	86.91
45	30	30	35	140	86.84	84.12	86.01	89.18
45	30	35	30	140	86.84	84.12	88.21	86.91
45	35	30	30	140	86.84	86.20	86.01	86.91
30	45	40	30	145	81.17	90.29	90.39	86.91
30	50	30	35	145	81.17	92.30	86.01	89.18
30	50	35	30	145	81.17	92.30	88.21	86.91
35	30	50	30	145	83.09	84.12	94.69	86.91
35	35	45	30	145	83.09	86.20	92.55	86.91
35	40	30	40	145	83.09	88.26	86.01	91.42
35	40	35	35	145	83.09	88.26	88.21	89.18
35	40	40	30	145	83.09	88.26	90.39	86.91
35	45	30	35	145	83.09	90.29	86.01	89.18
40	30	30	45	145	84.98	84.12	86.01	93.66
40	30	35	40	145	84.98	84.12	88.21	91.43
40	30	40	35	145	84.98	84.12	90.39	89.18
40	30	45	30	145	84.98	84.12	92.55	86.91
40	35	30	40	145	84.98	86.20	86.01	91.42
40	35	35	35	145	84.98	86.20	88.21	89.18

Power of burner (kW)					Temperature at centre of zone (°C)			
Zone 1	Zone 2	Zone 3	Zone 4	Total	Zone 1	Zone 2	Zone 3	Zone 4
30	30	50	40	150	81.17	84.12	94.69	91.43
30	35	50	35	150	81.17	86.20	94.69	89.18
30	40	30	50	150	81.17	88.26	86.01	95.87
30	40	35	45	150	81.17	88.26	88.21	93.66
30	40	40	40	150	81.17	88.26	90.39	91.43
30	40	45	35	150	81.17	88.26	92.55	89.18
30	45	30	45	150	81.17	90.29	86.01	93.66
30	45	35	40	150	81.17	90.29	88.21	91.43
35	30	35	50	150	83.09	84.12	88.21	95.87
35	30	40	45	150	83.09	84.12	90.39	93.66
35	30	45	40	150	83.09	84.12	92.55	91.43
35	35	30	50	150	83.09	86.20	86.01	95.87
35	35	35	45	150	83.09	86.20	88.21	93.66
35	35	40	40	150	83.09	86.20	90.39	91.43

- Different burner powers can lead to the same achievement in terms of the target amount of water evaporated.
- A higher power at the entrance side of the oven can lead to reduced energy consumption compared to evenly distributing the power across the oven or setting a higher power at the exit side of the oven.
- For example, setting the powers at Zones 1 to 4 to 40kW, 40kW, 30kW and 30kW, respectively uses only 140kW of power but setting them to 35kW, 35kW, 40kW and 40kW, respectively uses 150kW of power. This corresponds to a 6.7% decrease in energy consumption.
- The setting of 40kW, 40kW, 30kW and 30kW gives a more uniform temperature distribution across the oven. However, the overall temperature is not lower.

Some Findings and Recommendations

- The heat transfer due to radiation is about 500 times smaller than that due to conduction and convection. Thus, it can be ignored in the modelling.
- The end of the oven where wet formers enter will have a higher humidity than the end where dry formers exit the oven. Temperature profile is also non-uniform. Thus, it may be a good idea to provide non-uniform burner power across the length of the oven. Burner powers should be optimized to achieve the target requirement in terms of amount of water evaporated.
- The amount of water evaporated increases with burner power, because higher power increases the temperature and provides more energy for evaporation. It decreases with linespeed since the higher the speed, the less time the glove former spends inside the oven.

- The pattern of airflow justifies further studies. The direction and airflow may be different in different parts of the oven.
- The evaporation curve can be further investigated.

Outputs

Software program – copyright owned by Malaysia Rubber Council

Conference paper “Design of a Simulation Program to Model Vulcanization Ovens in Glove Manufacturing”, published at the International Conference on Robotics, Electrical and Signal Processing Techniques, 5 – 7 January 2021, pp. 428 - 432

Thank You

Q&A