Energy Consumption Reduction in the Condom Dipping Process: A Performance Comparison of Electric and Short-Wave Infrared Heating

Nares Chimres
Mechanical Engineering Program, Faculty of Engineering, Thaksin University, Phattalung, Thailand
nares.chimres@gmail.com

Utain Pattanapradit
Mechanical Engineering Program, Faculty of Engineering, Thaksin University, Phattalung, Thailand
utain89@gmail.com

Kittiphoom Suppalakpanya
Faculty of Agro-Industry, Rajamangala University of Technology Srivijaya, Nakhon Si Thammarat, Thailand
kittiphoom.s@rmutsv.ac.th

Ruamporn Nikhom
Energy Engineering Program, Faculty of Engineering, Thaksin University, Phattalung, Thailand
ruamporn6798@gmail.com (corresponding author)

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ABSTRACT

This study evaluates the energy performance of conventional Electric Heating (EH) and Short-wave Infrared Heating (SH) in the curing process of latex condoms. The findings demonstrate that SH significantly outperforms EH in terms of energy efficiency. Specifically, SH reduces energy consumption by 54.0%-71.7% for regular condoms and 38.8%-57.6% for thin condoms compared to EH. Both EH and SH meet the ISO 4074 standards for condom production, confirming that SH's efficiency gains do not compromise product quality. The consistent and superior energy performance of SH highlights its potential for improving cost-effectiveness and operational efficiency within the industry. While facilities currently using EH may achieve marginal benefits from upgrading to more advanced control systems, these improvements are relatively minor compared to the overall advantages offered by adopting the SH technology.

Keywords-condom manufacturing; short-wave infrared; curing process; Design of Experiments (DOE)

I. INTRODUCTION

Condom manufacturing has a significant impact on the rubber industry, particularly in the natural rubber latex sector, due to the high demand for latex-based products [1]. The production of high-quality condoms begins with the selection and processing of natural rubber latex or synthetic materials, such as polyurethane and polyisoprene [2]. Fresh natural latex is concentrated to achieve a 60% dry rubber content, then stabilized and blended with additives, including sulfur for the vulcanization process, accelerators, and antioxidants, to enhance durability and elasticity [3]. The characteristic condom shape is formed through a dipping process, where glass or ceramic molds are repeatedly immersed in the latex solution, dried, and subsequently cured via vulcanization at temperatures ranging from 100 °C to 130 °C [2, 4]. Vulcanization, a chemical process that creates cross-links between polymer chains, is crucial for producing elastic and tear-resistant condoms [5, 6]. Curing is a thermal or chemical process widely employed in material manufacturing to enhance physical, mechanical, or chemical properties [7, 8]. However, it is also one of the most energy-intensive stages due to the continuous heating required to activate the chemical reaction. Conventionally, expensive EH, which is commonly used in convective drying chambers [9], has been used to control heating parameters during this process. Reducing energy demand and cost during vulcanization, while maintaining high product quality, remains a major challenge in rubber processing

[10]. To address this, several efficiency-enhancing techniques have been developed. Accelerated cure systems employ optimized chemical formulations to reduce curing time and temperature requirements [11, 12], thereby lowering energy consumption. Moreover, microwave vulcanization offers a faster and more uniform heating process compared to conventional methods [13, 14]. Infrared curing has also shown promise, with benefits, such as improved energy efficiency and better adaptability over conventional convection technologies [15]. Additionally, hybrid approaches, such as combining infrared and hot-air heating for rubber glove vulcanization, have demonstrated improvements in mechanical properties while reducing energy use through more effective heat transfer [16]. Among infrared technologies, SH is particularly advantageous due to its rapid response times and reduced heat loss to the surrounding environment [17–20]. A performance comparison between SH and the conventional EH, presented in Table I, reveals that SH offers superior energy efficiency, faster processing times, and enhanced product quality. These benefits position SH as a more sustainable and effective solution for industrial thermal processing.

TABLE I. COMPARATIVE FEATURES OF EH AND SH

Feature	EH	SH
Heat transfer mechanism	Conduction and Convection	Radiative heating (infrared radiation)
Heating efficiency [19, 21]	Higher energy consumption and high energy loss to the surrounding air (indirect heating)	Lower energy consumption and low energy loss (direct heating)
Heating time [19]	Longer heating times due to indirect heating	Faster heating times due to direct heating
Temperature control [20, 21]	Gradual heating, slower response	Precise control, quicker response
Uniformity of heating [21]	Can be less uniform due to indirect heating	More uniform due to direct radiation
Product quality [20, 21]	Potential for less consistent quality	Potential for improved quality of thin-layer products due to uniform heating
System complexity	Generally simpler and well-established	Requires more advanced technology

While the benefits of SH have been recognized in various research contexts, its application at pilot-scale in latex condom production remains underexplored. Therefore, this study presents a comparative evaluation of SH and EH in the vulcanization stage of latex condom manufacturing. The investigation focuses on key performance indicators, including burst test volume, burst test pressure, and energy consumption. By optimizing heating parameters, such as temperature and duration, this study aims to assess whether SH provides a more efficient and reliable alternative to the conventional EH. The outcomes will inform future strategies for improving production efficiency and product quality in condom manufacturing.

II. EXPERIMENTAL SETUP AND PROCEDURE

To facilitate the latex dipping process for this study, a custom-built machine was developed specifically for testing and product development purposes. This machine was engineered to replicate the actual condom dipping and curing processes, closely simulating industrial manufacturing conditions. The energy consumption during the curing stage was measured using a Primus KM-22-1P7 watt-hour meter, known for its high accuracy and reliable calibration, thereby ensuring precise energy measurement.

The current study focused on the production of both regular (0.06-0.09 mm) and thin (0.06-0.07 mm) condoms exclusively produced for this experiment. By producing the condoms specifically for testing, the study ensured uniformity across samples and eliminated batch-to-batch variability. According to ISO 4074 standards, all condom samples were required to pass a volume burst test exceeding 18 L and a pressure burst test greater than 1.0 kPa.

The experimental procedure, illustrated in Figure 1, followed standard manufacturing steps. Each condom was initially dipped in a latex solution to form the base layer, then dried in ambient air, 2.3 min at 102 °C for regular condoms and 4.5 min at 63 °C for thin condoms. Then, a second dipping stage was performed to achieve the desired wall thickness after which the condoms were transferred to a curing station for final processing.

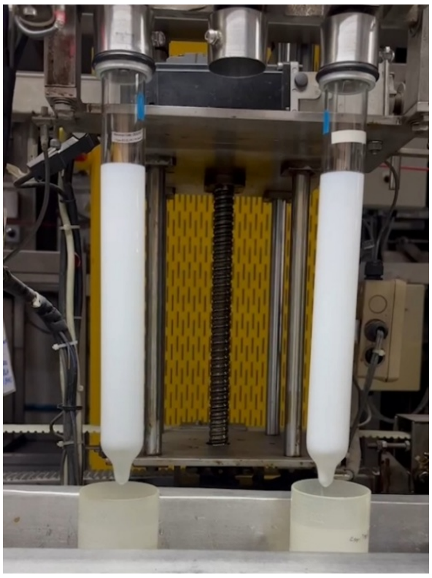
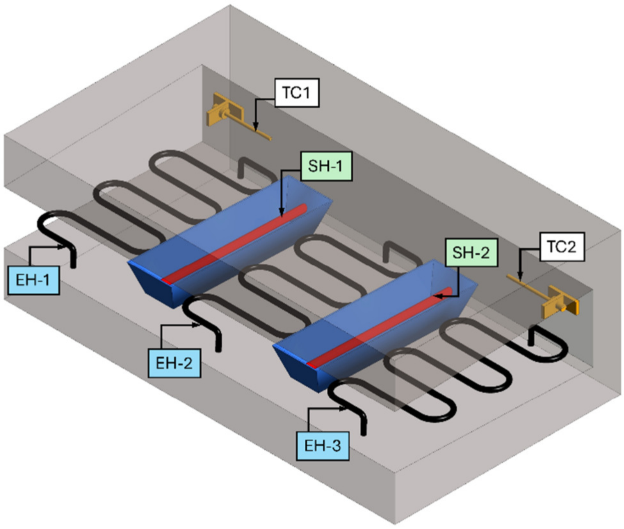


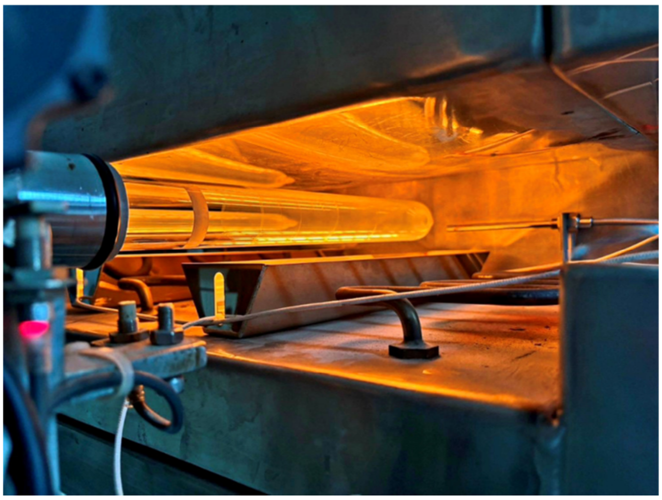
Fig. 1. Dip simulation machine.

Curing and drying were conducted in a controlled oven chamber, with temperature consistency ensured by a calibrated thermocouple. The chamber was equipped with two types of heaters for comparative evaluation: three 500 W EH and two 1000 W SH, as shown in Figure 2. The condoms cured using EH served as the baseline against which the SH-cured samples were evaluated. The SH units emitted radiation with a peak wavelength of 1.0-1.4 µm. Two type-T thermocouples, TC1 and TC2 (NI Model 9213), were positioned to measure the ambient air temperature within the curing chamber.

A full factorial Design of Experiments (DOE) was applied exclusively to the SH trials to systematically examine the influence of the key variables, mainly temperature and curing duration. Each experimental trial used two molds, producing two condoms per run. The DOE included two center points and two replications to ensure robustness and statistical validity.



(a)



(b)

Fig. 2. The configuration for the curing process: (a) schematic diagram, (b) experimental setup.

The experimental factors and their corresponding levels are summarized in Table II. Specifically:

- The Standard Order denotes the predefined sequence of experimental runs, as determined by the structure of the factorial design.
- The Run Order reflects the actual order in which the experiments were executed, often randomized to minimize the influence of uncontrolled external variables.
- The Center Point identifies the runs performed at the midpoint of the experimental factor ranges, enabling the detection of potential curvature or non-linearity in the response surface.
- The Block indicates groupings of experiments carried out under similar conditions, allowing for the control and assessment of systematic variability across different sets of experimental runs.

The selection of the curing temperature and curing time as experimental variables was based on their critical impact on the vulcanization process. The curing temperature, which varied from 95 °C to 105 °C, directly influences reaction kinetics and the extent of cross-linking within the latex matrix, hence affecting its final mechanical properties. Similarly, the curing time, ranging from 120 to 150 s, controls the duration of the vulcanization reaction. Inadequate curing time may lead to incomplete cross-linking, whereas excessive curing can degrade the material. Therefore, optimizing these parameters is essential to achieve a balance between energy efficiency and product quality in the curing stage.

TABLE II. DOE FOR CURING REGULAR AND THIN CONDOMS WITH EH AND SH

Standard order	Run order	Center point	Blocks	Temp (°C)	Time (s)
9	1	0	1	100	135
3	2	1	1	95	150
6	3	1	1	105	120
7	4	1	1	95	150
4	5	1	1	105	150
5	6	1	1	95	120
10	7	0	1	100	135
8	8	1	1	105	150
2	9	1	1	105	120
1	10	1	1	95	120

III. RESULTS AND DISCUSSION

The detailed analysis of the experimental results focused on key aspects relevant to the performance of SH compared to the conventional EH in the condom curing process. Three main areas were examined: i) heating efficiency and energy consumption, ii) curing efficiency and quality of condoms, and iii) statistical analysis of the process parameters. Each area was evaluated to understand the impact of the heating method on the operational performance, energy usage, and compliance with the quality standards.

A. Heating Efficiency and Energy Consumption

1) Comparative Analysis of Energy Consumption

The energy consumption of EH and SH was assessed exclusively during the curing phase of the condom manufacturing process. A summary of the energy usage for each heating method is presented in Table III.

The quality of both the regular and thin condoms cured by SH was found to be comparable to that of the condoms produced using the baseline EH, indicating that SH maintains product integrity while improving energy performance. On average, the energy consumed during curing with EH was 0.06 kWh per batch. In contrast, SH demonstrated substantially lower energy consumption, with reductions ranging from

54.0% to 71.7% for the regular condoms, and 38.8% to 57.6% for the thin condoms. The improved energy efficiency of SH can be attributed to its direct radiative heating, which reduces the heat loss and enhances the overall efficiency. The radiative heat transfer mechanism cured the condoms more quickly than the heat transfer by conduction and convection [21, 22], leading to lower energy usage.

TABLE III. THE ENERGY CONSUMPTION OF EH COMPARED WITH SH

Type of condom	Condition	Energy consumption (kWh)
Regular	EH	0.0565
	SH (max time - max temp)	0.0245
	SH (max time - min temp)	0.0205
	SH (min time - max temp)	0.017
	SH (min time - min temp)	0.016
Thin	EH	0.0425
	SH (max time - max temp)	0.026
	SH (max time - min temp)	0.0225
	SH (min time - max temp)	0.02
	SH (min time - min temp)	0.018

2) *Temperature Distribution*

The temperature distribution of the EH and SH systems was evaluated under both idle and curing conditions to assess the temperature stability and control accuracy of each method.

In the idle condition (no load of condom curing), EH displayed significant temperature fluctuations, as shown in Figure 3. The EH system, utilizing a basic on/off control mechanism, cycled between a maximum temperature of 138 °C and a minimum of 102 °C, on the right side, resulting in an average temperature of 117 °C and a high standard deviation of 8.96 °C, indicating high variability in temperature regulation. Such fluctuations were also observed on the left side of the heating unit, contributing to an inefficient energy use and potentially inconsistent thermal conditions during actual curing. In contrast, on the right side, SH maintained a more uniform temperature distribution, operating at 126 °C ± 3 °C, with a much lower standard deviation of 1.07 °C. This consistency is attributed to the advanced SH controller, which allows for precise modulation of the heating element. These findings are consistent with those in [23], where it was reported that infrared radiation promotes a uniform temperature profile during polymer curing processes.

During curing, the EH system continued to show notable temperature variability, as portrayed in Figure 4. On the right side, temperature ranged between 128 °C and 105 °C, with a standard deviation of 7.7 °C, while on the left side, it ranged between 118 °C and 97 °C, with a standard deviation of 6.9 °C. These fluctuations stem from the inherent limitations of the on/off control system, which cannot finely regulate the heat output. On the other hand, SH demonstrated a more stable performance, maintaining 118 °C ± 5 °C on the right side and 102 °C ± 4 °C on the left side, with corresponding standard deviations of 1.5 °C and 1.21 °C. This consistent temperature profile reflected the more precise regulation of SH that minimized the temperature variability seen in the EH system [24].

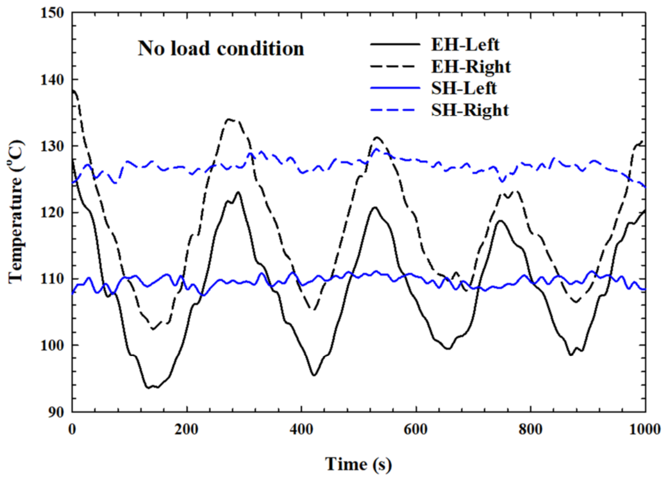


Fig. 3. Temperature distributions of EH and SH in the idle condition.

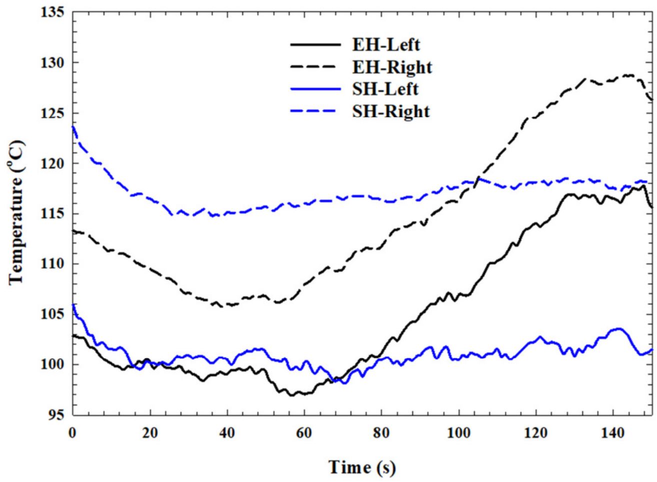


Fig. 4. Temperature distributions of EH and SH during curing.

B. *Curing Efficiency and Quality of Condoms*

1) *Volume and Pressure Burst Tests*

Volume and pressure burst tests, conducted following ISO 4074 standards, were employed to evaluate the mechanical integrity of condoms cured using both EH and SH. For the regular condoms cured using EH, the average volume burst test result was 35.75 L, and the pressure burst test result was 1.6 kPa. The condoms cured using SH showed slightly better performances, with a volume burst test result of 37.79 L and an average pressure burst test result of 1.77 kPa. For the thin condoms, SH also produced results comparable to those of EH. The baseline results from EH showed a volume burst test result of 32 L and a pressure burst test result of 1.45 kPa. While the SH-cured thin condoms achieved similar values, 32.5 L for the volume burst and 1.45 kPa for the pressure burst, three samples failed the pressure burst test, and two failed the volume burst test.

2) *Comparison of Curing Consistency*

The curing consistency was assessed by analyzing key performance metrics, namely energy consumption, pressure burst, and volume burst, under various curing conditions using SH. The results are presented in Tables IV and V for the regular and thin condoms, respectively, each corresponding to a specific combination of curing temperature and duration.

For the regular condoms (Table IV), all samples successfully met the ISO 4074 minimum criteria of ≥1.0 kPa for pressure and ≥18 L for the volume burst tests, indicating an overall consistent and reliable performance across curing conditions. However, minor inconsistencies were observed. Specifically, curing at 95 °C for 150 s and 100 °C for 135 s showed slightly lower volume burst values compared to other conditions. Additionally, one condition exhibited a marginal deviation in the pressure burst result. Despite these variations, no failures occurred, and all samples remained within acceptable quality thresholds.

The thin condoms (Table V) exhibited greater sensitivity to the curing condition than the regular condoms. This is an expected outcome due to their thinner membrane, which makes them more vulnerable to variations in temperature and time during the curing process. As a result, multiple failures were observed in the pressure and volume burst tests of the thin condoms. Specifically, at 100 °C for 135 s, two samples failed the ISO 4074 pressure test minimum requirement, bursting at pressures of 0.9 kPa and 0.95 kPa. Additionally, in the condition of 105 °C for 150 s, the test results were inconsistent: one sample failed with values of 0.8 kPa and 13.5 L, while another sample cured in the same condition passed with results of 1.45 kPa and 32.5 L, which exceeded the required standard.

TABLE IV. THE PRESSURE AND VOLUME BURST TEST RESULTS OF REGULAR CONDOMS CURED USING SH

Temp (°C)	Time (s)	Energy (kWh)	Pressure (kPa)	Volume (L)
95	120	0.016	1.9	42
95	120	0.016	1.9	41
95	150	0.02	1.45 (INCO)	33 (INCO)
95	150	0.021	1.85 (INCO)	41 (INCO)
100	135	0.019	1.8	40 (INCO)
100	135	0.019	1.7	34 (INCO)
105	120	0.017	1.7	40
105	120	0.017	1.85	40
105	150	0.023	1.95	40.5
105	150	0.026	1.9	36.5

INCO: Inconsistency

TABLE V. THE PRESSURE AND VOLUME BURST TEST RESULTS OF THIN CONDOMS CURED USING SH

Temp (°C)	Time (s)	Energy (kWh)	Pressure (kPa)	Volume (L)
95	120	0.02	1.3	26.5
95	120	0.017	1.35	28
95	150	0.022	1.2	24.5
95	150	0.023	1.1	23.5
100	135	0.022	0.9 (Fail)	17.5 (Fail)
100	135	0.022	0.95 (Fail)	18.5
105	120	0.02	1.3	27.5
105	120	0.02	1.4	29
105	150	0.026	0.8 (Fail, INCO)	13.5 (Fail, INCO)
105	150	0.026	1.45 (INCO)	32.5 (INCO)

INCO: Inconsistency

Despite these inconsistencies, several curing conditions yielded consistently acceptable results. For instance, curing at 95 °C for 120-150 s and 105 °C for 120 s produced uniformly compliant thin condoms, meeting both pressure and volume criteria. These findings underscore that while thin condoms require tighter process control, it is still possible to identify energy-efficient and quality-assured curing settings. The proper tuning of the curing parameters is, therefore, essential when producing thinner products to ensure consistency and compliance with standards.

C. Statistical Analysis

Analysis of Variance (ANOVA) was employed to determine the significance of temperature and curing time in the burst test outcomes.

1) Volume Burst Test Analysis

Tables VI and VII present the ANOVA results for the volume burst tests of the regular and thin condoms, respectively, cured using SH.

TABLE VI. ANOVA FOR VOLUME BURST TEST RESULTS OF REGULAR CONDOMS CURED BY SH

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	3	26.1000	8.7000	0.83	0.525
Linear	2	18.0000	9.0000	0.86	0.471
Temp	1	0.0000	0.0000	0.00	1.000
Time	1	18.0000	18.0000	1.71	0.238
Curvature	1	8.1000	8.1000	0.77	0.414
Error	6	63.0000	10.5000		
Lack-of-fit	1	4.5000	4.5000	0.38	0.562
Pure error	5	58.5000	11.7000		
Total	9	89.1000			

TABLE VII. ANOVA FOR VOLUME BURST TEST RESULTS OF THIN CONDOMS CURED BY SH

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	3	129.150	43.0500	1.39	0.334
Linear	2	36.125	18.0625	0.58	0.587
Temp	1	0.000	0.0000	0.00	1.000
Time	1	36.125	36.1250	1.17	0.322
Curvature	1	93.025	93.0250	3.00	0.134
Error	6	185.750	30.9583		
Lack-of-fit	1	2.000	2.0000	0.05	0.825
Pure error	5	183.750	36.7500		
Total	9	314.900			

The results for the regular condoms (Table VI) demonstrated that none of the investigated factors, namely temperature, curing time, or curvature, had a statistically significant effect on the volume burst performance at the 95% confidence level ($P < 0.05$). Among these, the linear term for time yielded the highest F-value (1.71), yet it remained non-significant ($P = 0.238$). Temperature showed no influence ($F = 0.00$, $P = 1.000$). The overall model was not statistically significant ($P = 0.525$), and the lack-of-fit test ($P = 0.562$) indicated that, despite the low explanatory power, the model appropriately fit the experimental data.

For the thin condoms (Table VII), a similar trend was observed. All three factors (temperature, curing time, and curvature) had a P-value above 0.05. Additionally, the overall model had a P-value of 0.334 and the lack-of-fit test a P-value of 0.825. These results suggest that the thin condoms, while potentially more sensitive to processing changes, did not show significant differences in volume burst performance within the tested curing conditions.

2) Pressure Burst Test Analysis

The pressure burst ANOVA results showed similar trends to those of the volume burst tests.

For the regular condoms (Table VIII), the overall model was not statistically significant (P = 0.856). None of the examined factors, namely temperature (F = 0.38, P = 0.560), time (F = 0.17, P = 0.695), or curvature (F = 0.21, P = 0.662), demonstrated a significant impact on the pressure burst values. The lack-of-fit test (P = 0.099) approached the conventional significance threshold, suggesting the presence of unexplained variability that may merit further model refinement.

For the thin condoms (Table IX), the model exhibited slightly more variability (F = 2.10, P = 0.202), with curvature (F = 4.17, P = 0.087) and curing time (F = 2.13, P = 0.194) showing a greater potential influence than temperature (F = 0.00, P = 1.000). However, none of these effects have achieved statistical significance. The lack-of-fit test (P = 0.874) indicated that the model adequately represented the experimental data.

TABLE VIII. ANOVA FOR PRESSURE BURST TEST RESULTS OF REGULAR CONDOMS CURED BY SH

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	3	0.022500	0.007500	0.25	0.856
Linear	2	0.016250	0.008125	0.27	0.769
Temp	1	0.011250	0.011250	0.38	0.560
Time	1	0.005000	0.005000	0.17	0.695
Curvature	1	0.006250	0.006250	0.21	0.662
Error	6	0.177500	0.029583		
Lack-of-fit	1	0.080000	0.080000	4.10	0.099
Pure error	5	0.097500	0.019500		
Total	9	0.200000			

TABLE IX. ANOVA FOR PRESSURE BURST TEST RESULTS OF THIN CONDOMS CURED BY SH

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	3	0.236250	0.078750	2.10	0.202
Linear	2	0.080000	0.040000	1.07	0.401
Temp	1	0.000000	0.000000	0.00	1.000
Time	1	0.080000	0.080000	2.13	0.194
Curvature	1	0.156250	0.156250	4.17	0.087
Error	6	0.225000	0.037500		
Lack-of-fit	1	0.001250	0.001250	0.03	0.874
Pure error	5	0.223750	0.044750		
Total	9	0.461250			

The absence of statistically significant effects across both condom types and both performance metrics may be attributed to the narrow range of the input parameters selected for the experiments. These ranges were established through preliminary trial-and-error screening, designed to ensure that all tested curing conditions produced condoms meeting the minimum quality specifications without failure. As such, the experimental domain was intentionally constrained to an optimized process window, excluding extreme conditions where product failure was known to occur. This constrained variability likely limited the observable range of responses within the DOE, reducing the statistical power to detect significant effects. Future research may benefit from expanding the tested ranges for curing temperature and duration to explore possible non-linear or threshold-dependent effects that could emerge under less conservative processing conditions.

IV. CONCLUSION

This study assessed the performance of Short-wave infrared Heating (SH) compared to conventional Electric Heating (EH) in the latex condom curing process. A full factorial Design of Experiments (DOE) was employed to evaluate the effects of curing temperature and time on both the energy consumption and product quality. The comparative analysis focused on the energy efficiency and compliance with the ISO 4074 standards. The key findings are summarized below:

- SH substantially improved the energy efficiency, reducing the energy consumption by 54.0%-71.7% for the regular condoms and 38.8%-57.6% for the thin condoms.
- The curing time was significantly reduced with SH, leading to greater production efficiency.
- The condoms cured with SH met the ISO 4074 standards in both volume burst and pressure burst tests.
- SH provided more stable and uniform temperature control, contributing to a consistent product quality across batches.

In conclusion, the results strongly support the adoption of SH as a viable and energy-efficient alternative to conventional methods in latex condom manufacturing. Its ability to maintain product quality while significantly reducing the energy use and curing time makes it a compelling option for sustainable and cost-effective production. Manufacturers are encouraged to consider transitioning to the SH technology to optimize their processes in terms of energy-saving, while maintaining quality assurance goals.

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