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Energy Efficiency and Thermal Performance Analysis of a Centrifugal Pump: Effect of Insulation Retrofit on Heat Loss Reduction

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Abstract: Centrifugal pumps are widely used in industry, agriculture, and the home. Their energy efficiency is determined by hydraulic losses, friction, and electrical losses in the drive system. This study experimentally examines the effect of external thermal insulation on the case heat transfer and the overall efficiency of a 0.5HP (0.373 kW) centrifugal pump. The suggested approach studies the case of an uninsulated pump at different insulation thicknesses – 5, 10, 15, 20 mm. The electric power, flow rate, head, surrounding temperature, fluid temperature, and case surface temperature are estimated to evaluate the hydraulic and thermal efficiency of the pump. The approximated heat loss from the case is observed to reduce from 31.5 W (uninsulated) to 16.8 W (with 20 mm insulation), suggesting a 46.7% reduction. The wire-to-water efficiency increases slightly from 12.25% to 12.28%. The findings suggest that insulating the external case might be successful in minimizing heat losses from the pump case. However, its effect on the overall efficiency of the pump seems to be small. The findings have to be considered within the framework of the measurement approach, experimental variability, and the necessity to ensure adequate cooling for the motor and other essential components.

Keynote: Centrifugal pump | Energy efficiency | Thermal performance | Heat loss | Insulation retrofit | Energy balance.

I. INTRODUCTION

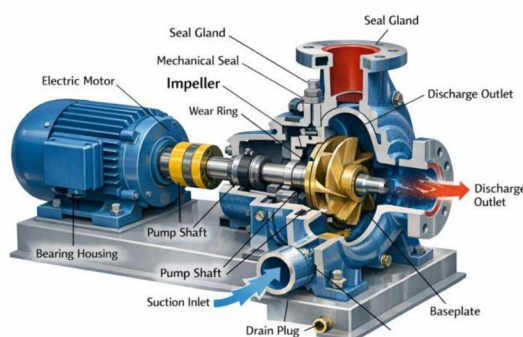
Centrifugal pumps are integral parts of fluid circulation, industrial production, agricultural irrigation, and water supply systems. The efficiency of electrical energy use, hydraulic efficiency, maintenance, and other factors affect the cost of pump operation. Therefore, the improvement of pumping systems and their energy efficiency is a relevant technical and economic task. Only a part of the electrical energy consumed by the pumping system is spent on the desired pumping process. The rest is lost due to the inefficiency of electric motors, friction processes, and hydrodynamic resistance present in the system. In addition, some energy is converted into thermal energy and dissipated into the environment through the pump casing by conduction and convection. Usually, insulation is used in piping systems, boilers, reservoirs, and other objects to reduce undesirable heat loss or gain. At the same time, the insulation of pump casings should be considered since some parts of the pump, such as electric motors, bearings, or seals, may require heat dissipation for stable operation. The current research aims to analyze the influence of external casing insulation on the thermal performance of the Centri pump. The pump under study has a power of 0.5 horsepower (HP). The unpainted pump casing is used as a reference point for comparison with other cases. An analysis of the dependence of the casing temperature, the amount of heat transferred from the casing, and the wire-to-water efficiency is performed. Four different insulation thicknesses, including 5, 10, 15, and 20 mm, were considered in the study. The choice of these objects for analysis is justified by the desire to find out the possibility of reducing the heat transfer from the casing by insulation, which will reduce the thermal load on the pump while ensuring the required level of hydraulic efficiency. The obtained results will contribute to further research in the field of thermal protection of centrifugal pumps.

II. LITERATURE REVIEW

Centrifugal pumps are widely used in industrial, agricultural, and domestic fluid handling systems, and their electric energy consumption represents a significant amount of the overall process energy consumption. Previously published works about centrifugal pump performance evaluation focused on hydraulic efficiency, best pump operating points, impeller geometry, pressure-head performance, and flow characteristics. Computational fluid dynamics and experimental research have been largely used to assess hydraulic losses and optimize the pump performance. However, most of the works lack the analysis of external heat losses from the pump casing.

Thermal and energy-performance investigations of rotating machinery demonstrate that it is crucial to monitor such parameters as electric input, useful energy, temperatures of different elements, and energy losses in order to estimate the performance of the actuator. In the case of centrifugal pumps, heat losses could be caused by hydraulic losses, mechanical friction, motor inefficiency, and fluid shear. The pump casing eventually dissipates some part of the heat energy into the environment. Hence, external heat losses and temperatures of the pump casing could potentially provide additional insights into the thermal performance of the pumping system.

To minimize unwanted heat loss from the pipeline elements, boilers, heat exchangers, tanks, and many other heat-generating objects, thermal insulation was studied thoroughly. Increasing the insulation thickness increases the thermal resistance and decreases the surface heat loss. However, the topic of applying various insulation thicknesses on the centrifugal pump casing under regulated working conditions has not been studied experimentally.



As a result, there is a knowledge gap in the controlled, uninsulated-to-insulated experimental quantification of casing heat loss reduction for small centrifugal pumps. A 0.5 HP (0.373 kW) centrifugal pump was studied in the present research to fill the mentioned gap. Under controlled working conditions, a comparative analysis of the pump performance was conducted: the first case studied the centrifugal pump without insulation, and the next four cases considered insulation thicknesses of 5, 10, 15, and 20 mm. The heat loss from the casing and % heat-loss reduction were analyzed experimentally, considering the electric, hydraulic, and thermal characteristics of the centrifugal pump to estimate the insulation performance as an energy-management technique.

III. THEORETICAL FRAMEWORK

Theoretical Framework

A. Overall Efficiency

$$\eta_{\text{overall}} = \frac{P_{\text{hydraulic}}}{P_{\text{in}}} = \frac{\rho \cdot g \cdot Q \cdot H}{P_{\text{in}}}$$

B. Energy Balance and Thermal Loss Fraction

Heat is transferred from the casing surface to the surrounding ambient environment by a combination of thermal radiation and natural convection.

$$\dot{Q}_{\text{surface}} = h_{\text{conv}} \cdot A_s \cdot (T_s - T_{\infty}) + \epsilon \cdot \sigma \cdot A_s \cdot (T_s^4 - T_{\infty}^4)$$

C. Estimated Heat-Loss Reduction (%) is

$$\text{Heat-Loss Reduction (\%)} = \frac{\dot{Q}_{\text{uninsulated}} - \dot{Q}_{\text{insulated}}}{\dot{Q}_{\text{uninsulated}}} \times 100$$

For your pump insulation experiment, the formula for

Where:

- $\dot{Q}_{\text{uninsulated}}$ = Heat loss from pump casing without insulation
- $\dot{Q}_{\text{insulated}}$ = Heat loss from pump casing with insulation

IV. METHODOLOGY

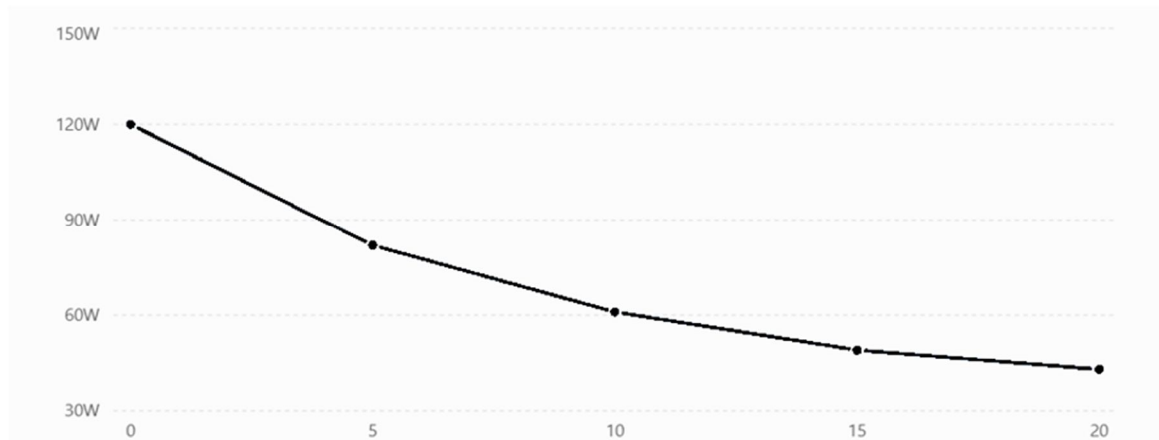
A. Experimental Setup

A 0.5 HP (0.373 kW) centrifugal pump coupled to a closed-loop water circulation system makes up the experimental apparatus. The primary electrical, hydraulic, and thermal characteristics needed for performance assessment are measured by the pump's instrumentation. To monitor input power, a digital power meter/energy analyzer is mounted at the electrical supply. Pressure gauges are placed at the suction and discharge sides to measure the pump head, and a flow meter is set in the discharge line to measure the volumetric flow rate. K-type thermocouples placed at specific points on the external pump casing are used to measure the temperature in addition to the ambient and water temperatures.

To determine the baseline hydraulic and thermal performance, the pump is first run without insulation. The chosen external casing surface is then covered with thermal insulation in thicknesses of 0, 5, 10, 15, and 20 mm. For every thickness of insulation, the same controlled operating conditions are used to repeat the trials. After the system reaches a stable operational condition, data are recorded for each test condition, including electrical input power, flow rate, suction and discharge pressure, ambient temperature, water temperature, and casing surface temperature.

B. Heat loss vs. insulation thickness

Illustrative trend showing how insulation thickness may affect casing heat loss.



Hydraulic output power, wire-to-water efficiency, casing surface temperature, anticipated external heat-transfer rate, and % reduction in casing heat loss are all calculated using the measured data. The impact of insulation thickness on the centrifugal pump's thermal performance is assessed by comparing the outcomes for the insulated settings with the uninsulated baseline.

C. Summary of Thermal Performance

Insulation Thickness	Average Casing Temperature (°C)	Temperature Reduction (°C)	Estimated Casing Heat Loss (W)	Estimated Heat-Loss Reduction (%)
0 mm	45.16	0.00	31.5	0.0
5 mm	41.60	3.56	25.8	18.1
10 mm	39.20	5.96	21.7	31.1
15 mm	37.20	7.96	18.9	40.0
20 mm	35.80	9.36	16.8	46.7

V. RESULTS

- 1) Thermal Performance of Pump Casing: With 20 mm of insulation, the average casing surface temperature dropped from 45.16°C in the uninsulated state to 35.80°C.
- 2) Change in Surface Temperature: The insulation effectively reduced heat dissipation from the pump casing by lowering the temperature by around 9.36°C.
- 3) Decrease in Casing Heat Loss: The thermal efficacy of the retrofit was confirmed by the predicted decrease in heat transfer from the casing to the surrounding environment as the insulation thickness rose.
- 4) Wire-to-Water Efficiency Analysis: Without insulation, the average wire-to-water efficiency was 12.25%; with 20 mm insulation, it was 12.28%.
- 5) Effect of Insulation on Pump Efficiency: There was barely a 0.03 percentage point increase in efficiency. As a result, insulation shouldn't be regarded as a key strategy for raising hydraulic pump efficiency.
- 6) Influence of Insulation on Pump Performance: Without altering the impeller, hydraulic channels, motor, or internal pump parts, the insulation can be applied externally.
- 7) Potential Applications of the Insulation Retrofit: Institutional water supply systems, laboratory pumping systems, and certain industrial applications are examples of situations where the suggested retrofit might be helpful in lowering external heat dissipation or regulating pump surface temperature.

VI. CONCLUSION

This study experimentally examined the energy efficiency and thermal performance of a centrifugal pump before and after a casing insulation retrofit. The findings showed a 46.7% decrease in casing heat loss, from 31.5 W to 16.8 W. The average wire-to-water efficiency improved by 0.03 percentage points, from 12.25% to 12.28%.

Although the observed improvement in total efficiency was rather moderate, the results show that casing insulation can significantly reduce thermal losses from the pump casing through a straightforward and inexpensive retrofit. This study's energy-balance methodology offers a methodical way to measure thermal losses, and it can be used for other rotodynamic and mechanical devices where thermal losses are an underappreciated part of overall energy consumption.

The suggested retrofit can be implemented in existing pumping systems as it does not require alterations to the hydraulic part of the pump. The retrofit evaluation in the context of variable-speed operation, different pump sizes and loads, prolonged operational conditions, and techno-economic analysis, including the cost of installation, energy savings, and payback period, will be the subject of future research.

VII. ADVANTAGES

- 1) Immediate energy recovery and cost savings: By reducing unwanted heat loss from the casing, this technique saves energy within the fluid circuit and lowers overall operating costs.
- 2) Low-cost retrofit: It offers an easily accessible, low-cost thermal management solution that can be retrofitted on existing, in-service pumps with minimal mechanical modifications.
- 3) Little installation overhead: Simple to apply, it avoids blocking key cooling features.
- 4) Improved environmental and thermal safety: By reducing the temperature of the external casing surface, it eliminates the risk of accidental thermal contact burns and reduces worker exposure by reducing ambient room heating, particularly in enclosed pump houses.

- 5) Non-invasive hydraulic performance: It maintains original hydraulic baseline characteristics, flows, and total dynamic heads while significantly reducing external thermal losses.

VIII. FUTURE SCOPE

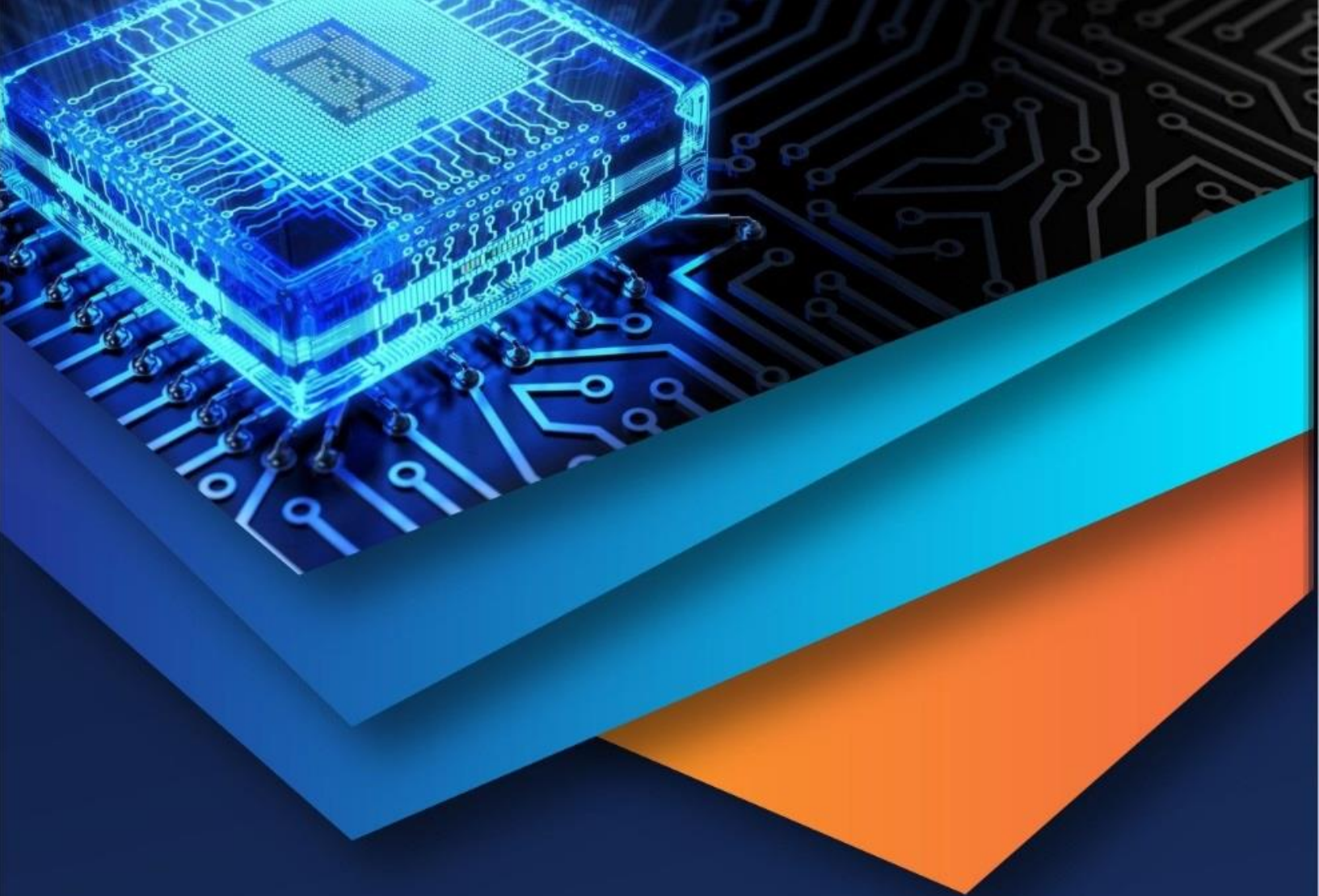
- 1) Thermal Analysis Under Variable Operating Conditions: Analysis of the thermal behavior during cold start, varying load, VFD operations, and long-run continuous duty cycles is termed Thermal Analysis Under Variable Operating Conditions.
- 2) Optimization of Insulation Materials and Thickness: The evaluation of innovative high-performance insulators like aerogels, ceramic fibers, or closed-cell elastomers to optimize thickness vs. thermal resistance ratios for compact spaces.
- 3) CFD-Based Thermal and Flow Analysis: The development of 3D integrated CFD-driven thermo-hydraulic simulations portraying time-dependent thermal variations, internal fluid friction heating, and casing conduction trends.
- 4) Validation Over Different Pump Operating Conditions: The inclusion of industrial high-capacity pumps operated under varying fluid thermal characteristics, such as multi-stage, double-suction, and high-temperature fluid pumps in the experimental testing protocol.
- 5) Infrared Thermal Imaging for Hotspot Detection: The enhancement of targeted insulation installation practices through the use of non-contact infrared thermal imaging to identify localized hotspots on complex case geometries.
- 6) Life-Cycle Economic and Environmental Assessment: The utilization of life-cycle assessments (LCA) and long-term techno-economic analyses to portray net payback durations, material longevity, and reduced carbon emissions.

IX. ACKNOWLEDGMENT

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