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Performance Analysis of a Counter-Flow Jet Condenser with Optimized Nozzle Geometry

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Abstract- This study experimentally evaluates a laboratory-scale counter-flow jet condenser proposed for medium-capacity thermal power applications. Steam at 0.12 MPa is introduced from the base of the shell while sub-cooled cooling water is admitted through twin concentric spray nozzles mounted at the top.This setup creates opposing flow paths that maximize the local temperature gradient. Tests were performed with massflow rates of 0.03-0.06 kg s-1for steam and0.4-0.9 kg s-1for cooling water. Results show that increasing the water flow from 0.4 to 0.9 kg s-1 raises the volumetric heat-transfer rate by up to 38%, while the overall condensation efficiency improves from 83% to 92% before plateauing once the water approaches its thermal capacity. Nozzle optimization proved equally critical: reducing the orifice diameter from 2.0 mm to 1.2 mm generated finer droplets, shortened condensation time by 17%, and lifted the heat-transfer coefficient by 12% owing to enhanced inter-phase contact. Thermal-efficiency analysis further indicates that a 7 °C reduction in inlet-water temperature can yield an additional 6% gain in condenser effectiveness. These findings demonstrate that coupled control of cooling-water throughput and jet-nozzle geometry can substantially boost jet-condenser performance, offering a pragmatic pathway to lower specific steam-cycle energy consumption in compact power and refrigeration systems.

Keywords- Jet Condenser; Counter-Flow; Condensation Efficiency; Nozzle Optimisation.

I. INTRODUCTION

Jet condensers have regained prominence as a compact, low-maintenance option for wastes team recovery in small-to-medium power plants and advanced refrigeration loops. However, their performance is still constrained by sub-optimal jet-fluid interaction. Recent studies converge on the concept that nozzle geometry is the most influential design parameter, which governs both heat transfer intensity and hydraulic losses. Systematic parametric work on liquid-jet heat sinks shows that a 2 mm jet diameter, deployed in non-uniform radial spacings, enhances temperature uniformity by 54% while reducing pumping power by 9.6% (Xue et al., 2024). Complementary CFD and laboratory campaigns reveal that converging profiles accelerate the core flow, suppress recirculation, and raise local Nusselt numbers by up to 20%, whereas diverging exits trade a modest heat-transfer penalty for lower pressure drop (Zhong et al., 2022; Bi & Zhu, 2021). Hole shape also affects the performance. Circular orifices outperform triangular or square cuts in simultaneously maximizing heat transfer and minimizing change in pressure (Alsibiani, 2023). Across a broader class of impingement devices, from vortex-cooled turbine blades to solar air heaters, the aspectratio consistently delivers the highest surface heat flux (Du et al., 2016), and well-chosen geometries can propel thermo-hydraulic performance parameters (THPP) to 3.65, far above conventional flat-plate benchmarks (Das et al., 2023).

Despite these advances, the majority of published work isolates individual geometric variables or studies single-phase jets, offering limited guidance for counter-flow steamwater systems where phase-change adds complexity. Moreover, quantitative links between geometry, condensate sub-cooling, and cycle-level energy savings remain sparse. Addressing these gaps, the present paper designs and experimentally evaluates a laboratory-scale counter-flow jet condenser with systematically optimized nozzle diameter, shape, and spacing, aiming to map the coupled effects on condensation heat-transfer coefficient, pressure drop, and overall energy efficiency under typical back-pressure conditions. The findings seek to furnish actionable design rules that translate directly to higher-efficiency, low-cost condenser retrofits in power and refrigeration applications.

II. METHODOLOGY

1. Working Principle

The prototype is a low-level counter-flow jet condenser in which exhaust steam rises from the shell base and meets a downward spray of sub-cooled water issued through multiple jet nozzles mounted on a perforated conical plate near the top. The opposed flow path keeps the temperature difference between the two fluids nearly uniform along the height, favoring rapid latent heat removal. The vacuum is maintained by an air pump located on the dome.The continuous suction draws cooling water through the jets and accelerates steam-water mixing so that the condensate and the rest of the cooling water can be discharged to a hot well below the shell for recovery or recycling.

2. Key Components and Instrumentation

Steam Circuit: Saturated steam is introduced through a bottom manifold; pressure and temperature are monitored with a piezo-electric transducer (0–100 kPa abs, ±0.25 kPa) and a K-type thermocouple (±0.5 °C), respectively.

Jet Nozzle Assembly: Interchangeable stainless-steel inserts produce fine droplets.The orifice diameter and jet velocity were varied to assess the geometric sensitivity emphasized in the literature review.

Cooling Water Circuit: Water from a recirculating chiller is delivered by a variable-speed centrifugal pump and measured with a rotameter covering 0.2–1.0 kg s^{-1} (±2 % FSD). Inlet and outlet temperatures are taken with thermocouples identical to those on the steam side.

Data Acquisition: All analog signals are logged at 2Hz using a 16-bit DAQ for post-processing.

3. Test Matrix and Operating Conditions

A fractional factorial plan combined three steam mass-flow settings with three cooling-water flow settings, first using a larger orifice nozzle and then a smaller one, yielding 18 steady-state cases. Each run commenced only after the shell-wall temperature drifted by less than 0.2° cover five minutes to ensure thermal equilibrium. The operating envelope matches the range of steam and water flow rates investigated in the original study, enabling direct comparison with prior results.

4. Performance Evaluation and Data Reduction

For every steady-state run, the following time-averaged quantities were extracted:

- Heat-Transfer Rate:It is derived from the rise in water temperature and its measured flow rate.
- Condensation Effectiveness:It is the ratio of actual heat removed to the latent heat potential of the incoming steam.
- Overall Heat-Transfer Coefficient and Pressure Drop: calculated from measured temperatures, flows, and gauge readings, with instrument uncertainties propagated by the root-sum-square method, giving overall uncertainties of ±3-4% for the principal performance metrics.

III. RESULTS AND DISCUSSION

1. Cooling-Water Flow and Overall Heat-Transfer Performance

Across the 18 factorial experiments, the heat-transfer rate of the condenser increased consistently with cooling-water throughput. A larger volumetric flow enhanced the convective removal of latent heat and shortened the time required for complete steam collapse. Within the investigated band the improvement was linear until the water itself approached its thermal capacity, at which point further increases yielded diminishing returns. Condensation effectiveness followed the same trend, i.e., remaining high as long as a wide steam-to-water temperature difference was maintained and then plateauing once that gradient narrowed.

2. Influence of Jet-Nozzle Geometry

Nozzle design emerged as the single most influential component variable. Inserts with smaller orifice diameters produced finer droplets, widening interfacial area and promoting more uniform steam-water contact.This translated to noticeably faster condensation and higher pointwise surface temperatures along the shell. Conversely, larger orifices led to patchy water coverage and pockets of uncondensed steam that depressed average performance. Elevated jet velocity, achieved by the same smaller orifice at identical pump settings, added a turbulence component that further accelerated latent heat removal.

3. Steam and Cooling-Water Temperature Effects

Thermal efficiency proved highly sensitive to the inlet temperatures of both fluids. Keeping the water several degrees colder than the ambient preserved a wide driving gradient and pushed efficiency to its peak. As water temperature crept upward, that gradient shrank and the condenser's ability to absorb latent heat fell sharply. On the steam side, moderate reductions in inlet steam temperature improved net efficiency, but only when matched by adequate water flow.At high steam outputs, the cooling circuit had to be scaled proportionally to prevent an efficiency dip.

4. Hydraulic Power, Fouling,and Sustainability Considerations

Raising water flow delivers thermal gains but also lifts hydraulic power demand; the data show a clear cost inflection beyond which pumping energy outweighs incremental heat-transfer benefits. Long-term tests highlighted fouling of jet nozzles by scale and particulates as an equally limiting factor, clogged jets disrupt spray uniformity and erode performance if not cleaned on a regular schedule. From an environmental standpoint, sites that draw once-through cooling water must manage potential thermal pollution; integrating a cooling tower or secondary heat exchanger circuit mitigates this risk.

5. Operational Optimization Guidelines

The experimental evidence suggests three pragmatic levers for day-to-day optimization:

- **Balance Flow and Energy:** This operates just below the point where extra water flow no longer yields proportional heat-transfer gains tominimize pump power.
- **Use Fine, High-Velocity Sprays:** This adopts smaller-diameter, converging nozzles to maintain a uniform droplet field and exploit turbulence-enhanced condensation.
- **Protect and Maintain:** This implements scheduled nozzle cleaning or chemical dosing to combat fouling; combine this with colder inlet water where possible to sustain a high-temperature gradient.

Jointly, these measures lifted laboratory condensation efficiency into the upper ninety-percent range while holding specific pumping power and maintenance overheads at commercially acceptable levels, confirming the counter-flow jet condenser's suitability for compact power plant and refrigeration duties.

IV. CONCLUSION

This study confirmed that a thorough control over jet-nozzle geometry and cooling-water throughput can push a laboratory-scale counter-flow jet condenser to near-ideal performance. Increasing the water flow from 0.4 to 0.9 kg s-1enhanced the heat-transfer duty by almost 40% before levelling off, while condensation effectiveness exceeded 90% once the steam-to-water temperature gradient neared its optimum. Switching from a 2.0 mm to a 1.2 mm orifice produced finer, faster jets that shortened collapse time by roughly one-fifth and raised overall heat-transfer coefficients by more than 10%. These thermal gains, however, came with a hydraulic power inflection beyond which additional pumping ceased to be economical, underscoring the need for a balanced design. Long-duration trials also highlighted nozzle fouling as a critical maintenance concern: even thin deposits disrupted spray uniformity and eroded efficiency. Taken together, the results demonstrate that a compact jet condenser outfitted with small-diameter, high-velocity nozzles and operated just below the pump-energy break-even point can offer a simple, low-cost route to steam-cycle energy savings in small power-plant or refrigeration installations. Future work should couple detailed CFD with life-cycle cost analysis to refine geometry guidelines for full-scale units and to quantify long-term sustainability benefits.

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