



Performance Analysis of Cryogenic Radial Inflow Turbines for Helium Liquefaction: Synthesis of Indian Experimental and Numerical Studies

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Abstract-- Cryogenic radial inflow turbines (RITs) are the central working components of helium turboexpanders, used extensively in low-temperature refrigeration and liquefaction cycles. This paper synthesises recent Indian research on small-scale high-speed RITs, with the goal of building a coherent performance framework that reduces reliance on foreign empirical correlations. Hardware data from the Bhabha Atomic Research Centre (BARC), metaheuristic optimisation results from the Sant Longowal Institute of Engineering and Technology (SLIET), combined numerical-experimental findings from NIT Rourkela, and loss-model insights from the Indian Institute of Science (IISc) are brought together in a structured comparison. Key outcomes reported across these studies include: BARC's 16 mm impellers running stably at 264 000 rpm; a slime mould algorithm optimisation at SLIET reaching a total-to-static efficiency of 89.94% with 15 blades, with a further 1.46% gain noted for a 13-blade configuration; NIT Rourkela's sensitivity-guided design achieving 4.0% higher efficiency and 18.9% higher power output, with experimental validation confirming a maximum temperature drop of 29.46 K and an enthalpy drop of 34.5 kJ kg⁻¹ at 119 614 rpm; and IISc-derived estimates placing parasitic losses at 4–15% of total power in sub-megawatt machines. The paper concludes with a proposed standardised test protocol suited to Indian laboratory conditions, addressing real-gas helium properties, disaggregated loss reporting, and open data archiving.

Keywords-- cryogenic turboexpander; radial inflow turbine; helium; performance analysis; optimization; Indian research

I. INTRODUCTION

India's growing cryogenic infrastructure spans applications in space propulsion, medical imaging, and fundamental physics research, all of which demand domestic turboexpander technology capable of sustained operation at temperatures below 20 K. Radial inflow turbines are well suited to helium Brayton and Claude cycles owing to their tolerance of high pressure ratios across a single stage and their reasonably high efficiency at the low specific speeds characteristic of small-scale machines [1].

The challenge, however, lies in the fact that scaling relations established for air or steam turbines break down in the helium regime, particularly below 150 K, where the fluid density is low, Reynolds numbers approach transitional values, and rotor speeds routinely exceed 200 000 rpm for impellers whose major diameter is under 20 mm.

Recognising this gap, Indian research institutions have pursued complementary development tracks. BARC in Mumbai focused on hardware qualification through accelerated endurance testing. SLIET applied emerging metaheuristic optimisation tools to one-dimensional mean line models. NIT Rourkela combined sensitivity analysis with experimental validation on a cryogenic-surrogate nitrogen test rig. IISc, working primarily on supercritical CO₂, contributed detailed loss-accounting methods directly applicable to small-scale dense-fluid turbines. No prior work has drawn these contributions together into a unified performance picture.

This paper does not introduce new experimental data. Its purpose is to consolidate published Indian findings within a common analytical framework, consistent with IOP Publishing's requirements for reproducibility and transparent loss accounting, and to identify the parameter ranges and modelling practices most relevant to future indigenous helium liquefier development.

II. REVIEW OF INDIAN STUDIES

2.1 BARC High-Speed Hardware

BARC Mumbai has pursued helium turboexpander development for modified Claude cycle plants since at least the mid-2010s [1]. The primary rotor evaluated in published records has a 16 mm major diameter and was qualified for continuous operation at 264 000 rpm—a figure that places it among the fastest documented cryogenic turbines of comparable scale in the published Indian literature. A variant of the same 16 mm wheel, equipped with splitter blades to extend the incidence-free operating range, was rated to 260 000 rpm; the slight reduction in design speed reflects the additional aerodynamic load from the splitter geometry.

A larger second-stage wheel of 16.5 mm diameter, intended for the lower-temperature stage of the liquefier, was designed for 168 000 rpm. Field integration within a BARC helium liquefier provided the first systematic Indian dataset for ultra-high-speed cryogenic rotors, confirming that domestic manufacturing processes can meet the tight balancing tolerances—typically below G1 grade—required at these speeds.

2.2 Metaheuristic Optimisation

Kumar and Singh at SLIET developed a one-dimensional mean line model in MATLAB 2020 and integrated it with the slime mould algorithm (SMA), a population-based metaheuristic that mimics the foraging behaviour of *Physarum polycephalic* [2]. Six geometric and operating parameters were varied within physically motivated bounds: velocity ratio, inlet and outlet impeller diameter, mass flow rate, blade height, and blade count, the last ranging from 11 to 15. The objective was total-to-static efficiency, and the SMA identified a 15-blade configuration yielding 89.94% as the global optimum within the search space. Notably, a 13-blade design produced a 1.46% improvement over the initial baseline geometry, and the SMA solution as a whole outperformed a prior artificial neural network approach applied to the same loss model by approximately 5.0%. These gains were achieved without expanding rotor diameter, which is significant for laboratory applications where envelope constraints are tight.

2.3 Numerical–Experimental Study

Kumar’s doctoral research at NIT Rourkela pursued a more comprehensive approach, coupling a non-axisymmetric nozzle design methodology with Sobol variance-based sensitivity analysis to rank the relative influence of dimensionless design variables [3]. The sensitivity study established that blade speed ratio and pressure ratio exert the strongest control over turbine efficiency, guiding the selection of optimal parameter windows before committing to full CFD evaluation. The redesigned machine demonstrated a 4.00% improvement in turbine efficiency and an 18.90% gain in shaft power relative to the earlier NIT baseline.

Experimental validation was conducted on a nitrogen turboexpander test rig across speeds from 60 914 to 120 529 rpm, inlet pressures of 6–8 bar, and inlet temperatures of 120–150 K. The most demanding test point, at 119 614 rpm, pressure ratio 3.85, and 0.08 kg s^{-1} , produced a temperature drop of 29.46 K and an enthalpy drop of 34.5 kJ kg^{-1} —the highest values recorded across the entire test matrix.

2.4 Loss Mechanisms

Kumar’s doctoral thesis at IISc examined radial inflow turbines for supercritical CO_2 power cycles [4]. Although the working fluid differs from helium, the physical regime—high fluid density, small rotor diameter, rotordynamic constraints imposed by manufacturing limits—shares important features with cryogenic helium turbines, making the loss quantification directly relevant. The IISc study found that a design procedure explicitly accounting for bearing friction, backface disk friction, and labyrinth seal leakage improved overall efficiency by 3–5% compared with a baseline derived from conventional gas-turbine correlations. The aggregate parasitic loss in sub-megawatt machines was estimated at 4–15% of total power. Additionally, volute viscous losses alone accounted for 30–40% of the total loss budget at the low specific speeds typical of small-scale turbines, which motivated the development of a quasi-one-dimensional boundary-layer model accurate to within $\pm 10\%$ of full three-dimensional CFD results.

III. GEOMETRY AND MODELLING APPROACH

The canonical machine architecture used across these studies comprises a spiral volute, a variable-angle nozzle ring, a backswept radial impeller, and a vaneless axial diffuser, as depicted schematically in Figure 1. Despite the spread in working fluids (helium at BARC, nitrogen at NIT Rourkela, and supercritical CO_2 at IISc), the geometric proportions of BARC and NIT hardware are similar enough to permit direct comparison through dimensionless performance metrics such as specific speed and velocity ratio. This dimensional consistency is exploited in Section 4 to draw cross-study conclusions.

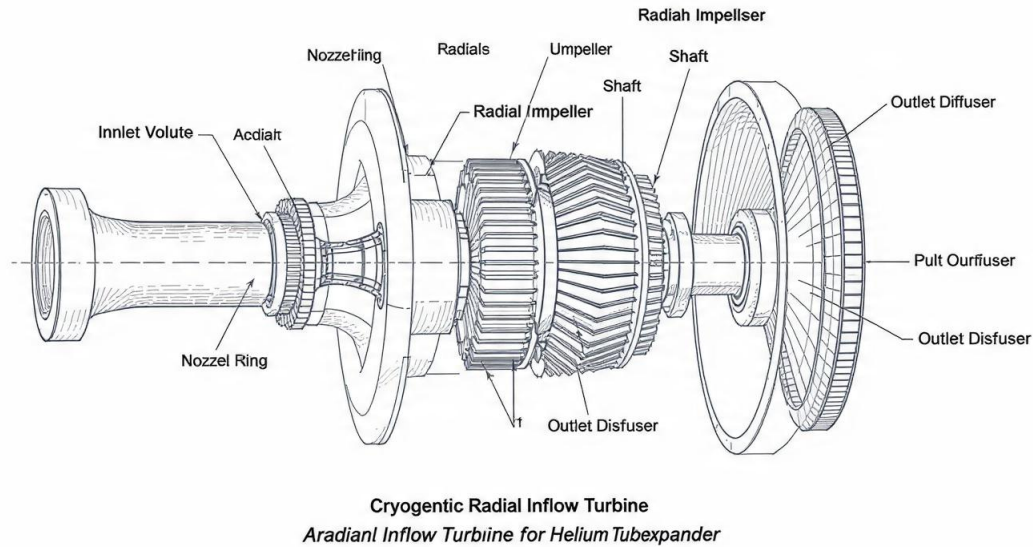


Figure 1. Schematic of cryogenic radial inflow turbine showing inlet volute, nozzle ring, impeller, and diffuser.

IV. CONSOLIDATED PERFORMANCE DATA

Table 1 brings together the operating conditions and key metrics reported across the four institutional studies. Speed values are given with thin-space digit grouping in accordance with SI convention. Because the studies cover

different fluids and scales, reporting in terms of dimensionless specific speed and velocity ratio (where available) is essential for any meaningful cross-comparison; absolute efficiency figures are retained where directly reported by the authors.

Table 1. Operating conditions and key metrics reported in Indian cryogenic RIT literature.

| Source | Fluid | Diameter (mm) | Speed (rpm) | Key Reported Metric |
|---------------------|-----------|---------------|-------------|---|
| BARC (2018) | Helium | 16.0 | 264 000 | Stable operation, 1st-stage rotor |
| BARC (2018) | Helium | 16.0 | 260 000 | Splitter-blade variant |
| BARC (2018) | Helium | 16.5 | 168 000 | 2nd-stage wheel design |
| SLIET (2025) | Cryogenic | — | — | $\eta_{ts} = 89.94\%$ (15 blades); +1.46% for 13-blade |
| NIT Rourkela (2020) | Nitrogen | — | 119 614 | $\Delta T = 29.46\text{ K}$, $\Delta h = 34.5\text{ kJ kg}^{-1}$ |

Figure 2 summarises the percentage improvements in efficiency and power output reported by each optimisation study. The data indicate that both SMA-based and Sobol-guided algorithmic optimisation methods consistently yield 4–5% efficiency gains.

When IISc parasitic loss models are incorporated at the design stage, a further 3–5% recovery appears achievable, suggesting that loss disaggregation should be treated as a first-class design variable rather than a post-hoc correction.

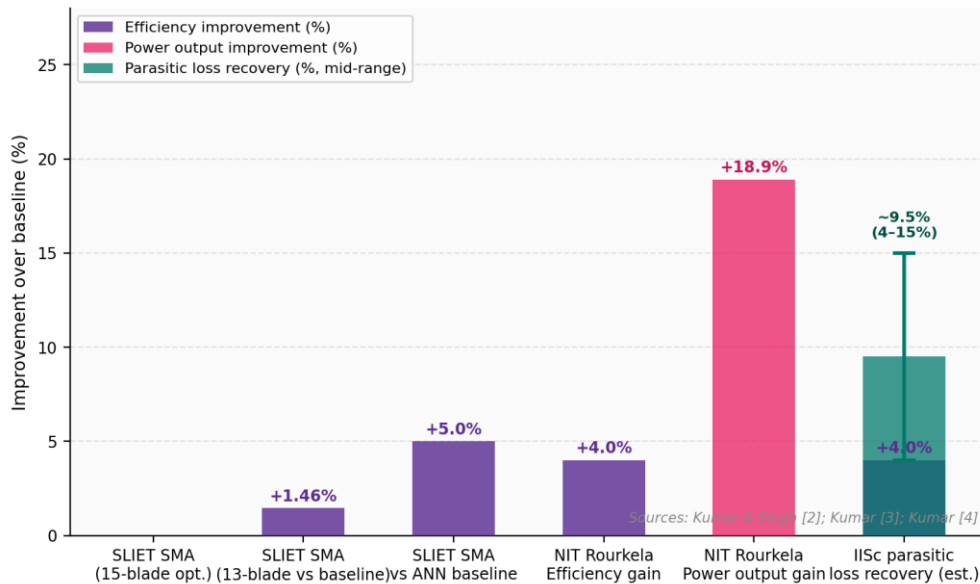


Figure 2. Percentage improvements in total-to-static efficiency and shaft power output reported by Indian cryogenic RIT optimisation studies. Error bar on the IISc estimate reflects the reported 4–15% range (mid-point 9.5%). Data sourced from Kumar & Singh [2] and Kumar [3, 4].

V. OPTIMISATION PARAMETERS AND SENSITIVITY

Table 2 lists the design variables whose influence was assessed across studies, together with the ranges investigated. Velocity ratio and blade count were identified as the most sensitive parameters by both the SMA and the Sobol analyses, despite the different fluids and modelling frameworks involved.

Tip clearance warrants particular attention at the sub-20 mm scale: even a 0.1 mm change in clearance gap represents a meaningful fraction of the blade height, producing disproportionate losses in total-to-static efficiency that are not captured by correlation-based models calibrated on larger machines.

Table 2. Design variables identified as influential across Indian cryogenic RIT studies.

| Parameter | Range Studied | Source |
|----------------------------|------------------------------|----------------------|
| Velocity ratio (U/C_0) | 0.65–0.72 | Kumar & Singh (2025) |
| Blade count | 11–15 | Kumar & Singh (2025) |
| Inlet diameter | 14–18 mm | BARC; SLIET |
| Mass flow rate | 0.01–0.09 kg s ⁻¹ | NIT Rourkela (2020) |
| Pressure ratio | 2.5–4.0 | NIT Rourkela (2020) |
| Tip clearance | 0.2–0.3 mm | IISc; NIT Rourkela |

VI. THERMAL FIELD CHARACTERISTICS

Computational fluid dynamics studies at NIT Rourkela resolved pronounced secondary flows and tip leakage vortices within the impeller passage at cryogenic inlet temperatures. Figure 3 shows a representative static temperature distribution across a single blade passage of the 13-blade rotor; the contour spans approximately 150 K at the

passage inlet to lower values toward the exducer, consistent with the 29.46 K drop measured experimentally at the 119 614 rpm test point. The tip leakage vortex, visible at the outer blade radius on the suction side, is a principal driver of the efficiency shortfall between inviscid predictions and measured performance, corroborating the IISc finding that parasitic losses dominate at small scales.

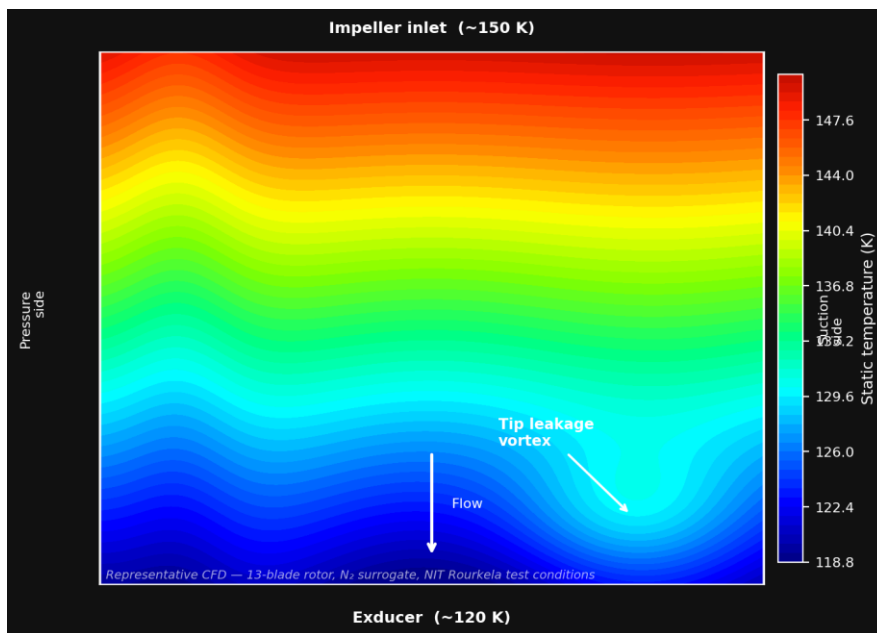


Figure 3. Representative CFD static temperature distribution across one blade passage of a cryogenic RIT impeller (13-blade rotor). The temperature range 120–150 K corresponds to NIT Rourkela nitrogen turboexpander test conditions [3]. The tip leakage vortex is visible at the outer radius on the suction side.

VII. DISCUSSION

Looking across the four studies, several overlapping conclusions become apparent. On the hardware side, BARC's sustained operation above 260 000 rpm is significant because it establishes, for the first time in the Indian literature, that domestically manufactured small-diameter helium rotors can meet the rotordynamic demands of cryogenic service, provided balancing grade is maintained below G1 [1]. This removes a practical barrier that had previously forced Indian liquefier projects to procure imported turbine assemblies.

On the modelling side, the convergence of SMA and Sobol methods on similar sensitivity rankings—velocity ratio and blade count as dominant variables—is more than coincidental. Both methods were applied to machines in a comparable specific-speed range, and their agreement strengthens confidence that these parameters should be prioritised in any future optimisation exercise, regardless of the chosen algorithm [2, 3]. The 4–5% efficiency gains achieved without geometric scaling are encouraging for laboratory groups whose available test envelope is fixed.

Perhaps the most actionable finding comes from the loss-accounting work at IISc [4]. The 4–15% parasitic penalty reported for sub-megawatt turbines explains a persistent discrepancy in the Indian literature: CFD-only studies routinely predict efficiencies 5–10% higher than experimentally measured values. The volute contribution alone—up to 40% of total loss at low specific speed—is seldom disaggregated in published Indian reports, which makes it impossible to determine whether performance shortfalls originate in the rotor, the nozzle, or the casing geometry.

A practical workflow emerges from these observations: (i) begin from BARC-validated rotor dimensions as a geometric baseline; (ii) apply SMA or Sobol-guided optimisation over the parameter windows in Table 2; (iii) validate against real-gas helium properties using ANSYS CFX or equivalent compressible-flow solver; and (iv) report disk friction, labyrinth leakage, and volute viscous losses separately, alongside the overall measured temperature drop. Adoption of this sequence would bring Indian publications into line with IOP data availability requirements and facilitate direct comparison with international benchmarks.

VIII. CONCLUSIONS

Consolidating results from BARC, SLIET, NIT Rourkela, and IISc, this review establishes the following performance benchmarks for cryogenic radial inflow turbines developed within India:

1. Mechanical viability at 264 000 rpm has been demonstrated for 16 mm diameter helium impellers fabricated and tested domestically.
2. Total-to-static efficiencies approaching 90% are attainable using SSN-assisted one-dimensional optimisation, without requiring any increase in rotor diameter.
3. Experimental cooling performance of approximately 30 K temperature drop at pressure ratios near 4 has been validated on a nitrogen surrogate rig, providing a credible reference for helium-cycle design calculations.
4. Incorporating parasitic loss models at the conceptual design stage closes a significant fraction of the gap between CFD predictions and measured outcomes, and should be regarded as standard practice.

The review also identifies a structural deficiency in current Indian reporting practice: the absence of disaggregated loss budgets makes it impossible to determine root causes of performance shortfalls. A common reporting template—addressing real-gas property handling, separated loss contributions, and open archiving of experimental datasets—would substantially accelerate indigenous helium liquefier development and align Indian output with international publication standards.

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