

Field reconstruction of Joule–Thomson cooling, hydrate risk and preheating efficiency at a natural gas pressure-regulating station

Frank Barimah Appiah-Adjei

frankappiahadjei60@gmail.com

University of Mines and Technology

Ohenewaa Kakra Dankwa

University of Mines and Technology

Victor Nketiah-Anning

University of Mines and Technology

Titus Fiifi Appiah

University of Mines and Technology

Research Article

Keywords: Joule-Thomson cooling, gas hydrates, pressure-regulating station, preheating, energy efficiency, natural gas transmission, field data

Posted Date: September 21st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10957893/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Field reconstruction of Joule–Thomson cooling, hydrate risk and preheating efficiency at a natural gas pressure-regulating station

Frank Barimah Appiah-Adjei, Ohenewaa Kakra Dankwa, Victor Nketiah-Anning, Titus Fiifi Appiah
Department of Petroleum Engineering, GNPC School of Petroleum Studies, University of Mines and
Technology, Tarkwa, Ghana

Corresponding author: Frank Barimah Appiah-Adjei, frankappiahadjei60@gmail.com

ORCID: 0009-0005-1468-6159

Abstract

Pressure-regulating stations preheat natural gas to offset Joule–Thomson (JT) cooling and keep the stream clear of hydrate-forming conditions. Heating is typically governed by a fixed bath setpoint rather than by the time-varying thermal demand of an individual letdown stream, so neither the safety margin actually maintained nor the heat actually delivered is known from design calculations alone.

The thermodynamic and energy behaviour of the principal letdown stream at an operating West African station was reconstructed for every valid hour of a 92-day period (2,157 valid station-hours) from operator shift logs and daily gas-chromatograph records. Each letdown was modelled as an isenthalpic expansion using the Peng–Robinson equation of state with the day’s measured composition, cross-checked against GERG-2008; hydrate equilibrium was estimated with a gas-gravity correlation and a rigorous Kladau–Sandler model. Delivered preheat duty was compared with the minimum duty required to hold defined safety margins, and the reconstruction was validated forward against an independently measured outlet temperature.

Four findings emerge. First, JT cooling is a stable, measurable property of the stream (effective coefficient $0.561\text{ }^{\circ}\text{C bar}^{-1}$, monthly range 0.552–0.568). Second, without preheating the stream would have lain within the calculated hydrate stability region in 98% of hours on the as-modelled basis, and in 85–98% of hours

across the full range of model corrections, establishing preheating as the sole barrier acting at the letdown point. Third, delivered duty exceeded the minimum required for a +5 °C margin by 85% on average (0.89 against 0.48 MW), amounting to 883 MWh of excess thermal duty over the study period, or 49% and 510 MWh on the heater-side duty basis. Fourth, despite that average surplus the margin fell below the +5 °C design threshold in 11 hours, all of them overnight, and in those hours delivered duty had collapsed to 0.379 MW while demand remained unremarkable at 0.483 MW. Metered fuel flow is uncorrelated with the stream's thermal demand ($r = 0.05$) while bath temperature holds near 59.6 °C.

Common-header preheating can produce excess thermal duty and residual hydrate-safety vulnerability at the same time, because aggregate heater control does not track the demand of individual letdown streams. The binding constraint is therefore the control architecture rather than heater capacity, and stream-level trim control merits evaluation. The analysis further shows that routinely kept operator records can support a reconstruction of this kind after structured quality screening.

Keywords: Joule-Thomson cooling; gas hydrates; pressure-regulating station; preheating; energy efficiency; natural gas transmission; field data

1 Introduction

Natural gas pressure-regulating stations are the interface between high-pressure transmission systems and downstream distribution networks. Pressure is reduced across regulating valves to meet delivery requirements, and because the expansion is approximately isenthalpic the associated Joule-Thomson (JT) effect cools the gas typically by 0.4-0.6 °C per bar for lean natural gas [1, 2]. Where the resulting temperature approaches or falls below the hydrate-equilibrium temperature at the downstream pressure, gas hydrates can obstruct regulators, instrumentation and pipework, interrupting delivery and creating safety

hazards [3]. Indirect water-bath heaters are therefore installed upstream of the regulating valves to raise the gas temperature before pressure reduction.

Although preheating is necessary for hydrate-risk management, the heating requirement is not constant. It varies with inlet pressure, outlet pressure, gas composition, flow rate and the hydrate-equilibrium condition of the gas. In practice, heating systems at these stations commonly operate from fixed or conservative bath-temperature settings rather than from the real-time thermal demand of an individual letdown stream. This creates an operational trade-off: insufficient heating erodes the hydrate safety margin, whereas excessive heating increases fuel consumption and thermal losses. A station may therefore experience inadequate protection during high-demand periods and unnecessary heating during lower-demand periods. As this study shows, it may experience both. Three strands of prior work bear on this problem. The first concerns the JT-hydrate coupling itself. Expansion cools the stream, promotes condensation of trace moisture and supplies the free water that hydrate nucleation requires; the mechanism has been resolved experimentally in purpose-built expansion facilities instrumented either side of the valve, in which wet gas plugged immediately downstream of the expansion point and faster than existing software tools predicted [4, 5]. Prediction of the hydrate boundary spans a hierarchy of models, from gas-gravity correlations suited to rapid screening [6] to rigorous van der Waals-Platteeuw statistical-thermodynamic formulations [3, 7], the latter now available in validated open-source implementations [8].

The second strand addresses the energy cost of hydrate avoidance. Indirect water-bath heaters operate at low thermal efficiency commonly reported below 40% and their improvement or replacement has become a research programme in its own right, recently surveyed by Deymi-Dashtebayaz et al. [9]. Reported routes include heater thermal redesign and fuel-consumption modelling [10], heat-transfer enhancement within the heater [11], derivation of the minimum admissible regulator inlet temperature so that heating is no greater than hydrate avoidance demands [12], control systems that compute the hydrate temperature online and modulate firing accordingly [13], and geothermal or solar-assisted integration [14, 15]. A related body

of work recovers letdown pressure energy with turboexpanders [16], which deepens JT cooling and therefore raises the preheating requirement, coupling the efficiency question back to the hydrate constraint. The third strand comprises analyses grounded in real station operation. Deymi-Dashtebayaz et al. [17] optimise fuel consumption at a named operating station on an explicitly hydrate-temperature basis, reporting savings of order 35%. Olfati et al. [18] characterise the energy and exergy behaviour of an operating city gate station across seasons and identify the regulator as the most exergy-destructive component despite its high energy efficiency. Olfati et al. [19] extend this into a demand-following preheating concept, computing the minimum preheat temperature for hydrate avoidance and disengaging the heater above it, with modelled reductions of at least 33% in energy consumption and above 80% in CO₂ emission. Rastegar et al. [20] develop predictive models for pressure-reduction-station outlet temperature with the explicit aim of reducing energy loss, and operational records from regulator stations have been shown to support data-driven anomaly detection [21]. Hydrate risk in West African gas infrastructure has been examined at the pipeline and flow-assurance scale, where formation is linked to internal corrosion and integrity threats [22].

What these studies share is an evaluative frame: each proposes or assesses a control strategy, design modification or predictive model, and does so at design points, seasonal averages or over short case-study windows, generally under a fixed or assumed gas composition. The complementary question addressed here is operational rather than prescriptive: over a continuous period of realised operation, how closely does the heating regime of a station track the thermodynamic demand of an individual letdown stream, and what margin is in fact maintained?

The contribution of this study is the integration of established methods into a single hour-resolved field reconstruction: JT cooling, hydrate equilibrium, stream-level thermal demand and common-header heater behaviour, evaluated over 2,157 measured station-hours using each day's own measured gas composition, and supported by equation-of-state cross-checking, hydrate-model benchmarking, explicit data-quality screening, uncertainty analysis and an in-service high-differential validation event. Individually these

methods are established; their combination on a single operating stream over a continuous 92-day period, together with a forward validation of the reconstruction against an independent in-service temperature measurement, is what this study adds.

The central proposition tested is that a common-header heating architecture serving heterogeneous letdown streams can produce a structural mismatch between aggregate heater control and individual-stream thermal demand. Such a mismatch would manifest as simultaneous over-provision of heat on average and periods of reduced hydrate safety margin. Demonstrating this behaviour from measured operating data provides a firmer basis for stream-level control than a design-point energy calculation alone.

1.1 Research questions

1. RQ1. What Joule-Thomson cooling behaviour does the study stream exhibit under its measured operating pressure, temperature and gas-composition conditions?
2. RQ2. What hydrate-equilibrium exposure would the study stream experience under the observed operating conditions in the absence of preheating, and what margin is actually maintained during operation?
3. RQ3. How does the thermal duty delivered to the study stream compare with the minimum duty required to maintain defined hydrate-safety margins?
4. RQ4. Does the observed heater-firing behaviour respond to the thermal demand of the study stream, or is it more consistent with aggregate control of the common heating header?
5. RQ5. Are the reconstructed conclusions robust to gas-composition uncertainty, instrument uncertainty, model choice and the selected safety margin?

2 Methods

2.1 Station, study design and boundary

The study is a retrospective longitudinal field-data analysis of a natural gas pressure-regulating station in West Africa, anonymised as Station X. The station receives high-pressure gas, preheats it in a water-bath heater serving a common heated header, and reduces pressure through several parallel letdown streams operating at different outlet pressures. The analysis is deliberately restricted to the principal delivery stream in order to maintain a clearly defined thermodynamic and mass-flow boundary. That stream regulates to a mean outlet pressure of 35.6 barg at a mean throughput of 84.4 MMscfd. During the study period inlet pressure ranged from 52.9 to 79.9 barg and inlet temperature from 22.0 to 26.2 °C.

Figure 1 shows the station arrangement and the location of each measured quantity. Two thermodynamic paths are distinguished throughout. The counterfactual path runs from the measured station inlet condition, upstream of the heater, and yields the outlet temperature that would obtain without preheating. The forward path runs from the measured heater outlet temperature, which is the regulator inlet, and yields a prediction that can be tested against the measured outlet temperature.

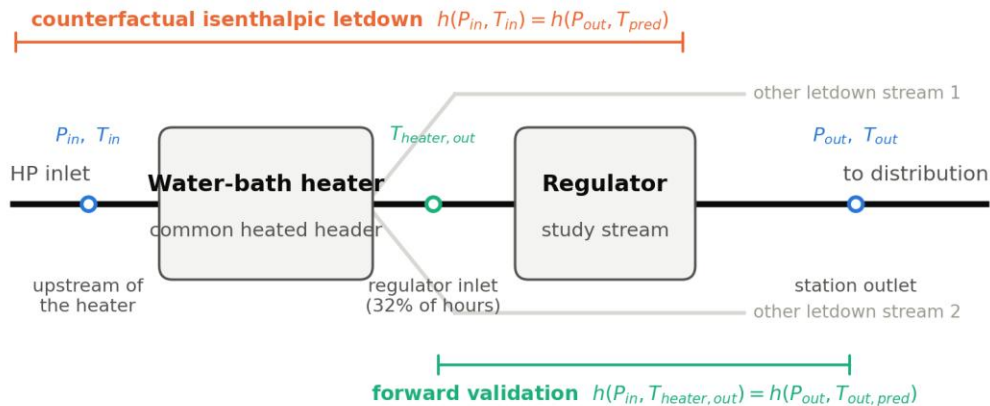


Fig. 1 Station arrangement, measurement locations and the two reconstruction paths. The counterfactual path (orange) establishes the no-preheating condition; the forward path (green) provides the validation of Section 3.6.1.

2.2 Study period and unit of analysis

The study covers 92 consecutive calendar days from 1 August to 31 October 2025. One day's records were absent from the archive, so the 2,208 possible station-hours yielded 2,184 hourly operator observations, of which 2,157 (98.8%) were retained after structured quality screening (Section 2.3). The station-hour is the unit of analysis because it permits the reconstructed thermodynamic state, hydrate margin and thermal demand to be evaluated against the operating conditions recorded for the same interval.

2.3 Data sources and quality screening

Primary data are hourly operator log sheets recording inlet and outlet pressure, inlet and outlet temperature, and instantaneous and accumulated flow. Secondary data are daily gas-quality records providing composition from C1 to C6 with N₂ and CO₂, specific gravity, heating value and water-vapour content; and heater and fuel-skid logs providing heater outlet and bath temperatures and station-level fuel-gas flow. All 99 archived daily workbooks were batch-parsed; eight undated template files were excluded and one calendar day was absent.

Quality screening was applied before thermodynamic reconstruction rather than after results were generated, and records identified by the screening were flagged and excluded rather than silently corrected. The procedure comprised completeness checks, physical-range checks, statistical outlier screening using the median absolute deviation (MAD), and consistency checks on accumulated flow. Table 1 reports the screening outcome.

Table 1 Data-quality screening of hourly station records

Screening stage	Records in	Excluded	Retained
Hourly operator records, 1 Aug – 31 Oct 2025	2,184	—	2,184
1. Completeness: core P/T channel missing	2,184	7	2,177
2. Physical-range validity: core P/T	2,177	20	2,157
3. MAD outlier screen, core P/T (flagged, retained)	2,157	0	2,157
4. Flow-channel screen (duty suppressed, hour retained)	2,157	0	2,157
Retained for thermodynamic reconstruction		27	2,157

The 27 exclusions comprise inlet-temperature range failures (14), inlet-pressure range failures (4), missing inlet temperature (3), missing outlet pressure (3), outlet-pressure range failures (2) and missing inlet pressure (1). A further 325 hours carried a MAD flow-outlier flag and 24 carried pressure or temperature outlier flags; these were retained, because at a delivery station the flow channel tracks genuine downstream demand and MAD flagging on flow identifies load excursions rather than measurement faults. Only physically impossible values were removed from the duty calculation: two flow readings of 5,091 and 8,483 MMscfd against an 84 MMscfd baseline, and two zero-flow hours. Duty statistics are therefore reported for 2,153 hours and margin statistics for 2,157.

Gas-composition records were validated by recomputing specific gravity from the reported mole fractions and requiring agreement with the laboratory-reported value within 0.005 (Table 2). Nineteen of the 91 daily records proved internally inconsistent. Two of these were gross failures whose mole fractions summed outside 95–105%: both are decimal-point transcription errors in n-pentane, recorded as 13.0 mol% on 24 October (sum 112.87%, implying a specific gravity of 0.857 against a reported 0.65) and 9.0 mol% on 26 October (sum 108.90%). These two records were rejected and the nearest preceding accepted composition substituted. The remaining 17 records failed only the specific-gravity cross-check while their mole fractions summed correctly; because the composition itself was internally consistent, these were retained and the discrepancy treated as an error in the reported specific-gravity field. Sensitivity of the conclusions to this choice is examined in Section 3.6.

Table 2 Gas-composition record validation

Criterion	Records
Daily gas-chromatograph records available	91
Parseable, complete C1–C6 / N ₂ / CO ₂ slate	91
Rejected: mole-fraction sum outside 95–105%	2
Passed specific-gravity cross-validation, $ \text{computed} - \text{reported} < 0.005$	72
Failed specific-gravity cross-validation, composition retained	17
Total internally inconsistent	19

2.4 Thermodynamic reconstruction

The pressure reduction is represented as an isenthalpic expansion. For each station-hour the predicted outlet temperature in the absence of preheating, T_{pred} , satisfies

$$h(P_{in}, T_{in}) = h(P_{out}, T_{pred}) \quad (1)$$

Mixture enthalpies and heat capacities are evaluated with the Peng–Robinson equation of state [23] as implemented in CoolProp [24], using each day’s measured composition. The mixture is represented by ten components: methane, ethane, propane, iso- and n-butane, iso- and n-pentane, n-hexane, nitrogen and carbon dioxide, with the C6 fraction treated as pure n-hexane; water is excluded from the equation-of-state composition and handled separately in Section 3.6.5. Van der Waals one-fluid mixing is used with all binary interaction parameters at the CoolProp cubic-backend default of zero. The consequence was quantified rather than assumed: re-solving a representative hour with literature binary interaction parameters for the eleven most significant pairs shifts the predicted outlet temperature by less than 0.1 °C, so the systematic offset against GERG-2008 reported in Section 3.6.2 is a property of the cubic enthalpy departure rather than of the omitted interaction parameters. Equation (1) is solved by Newton iteration, with the isobaric heat capacity as the derivative, to a tolerance of 0.01 K. The phase condition of the outlet states was checked against the mixture dew temperature computed from the same equation of state and composition. Every as-operated outlet state lies in the single-phase vapour region by a wide margin (minimum 17.6 °C, median 34.4 °C above the dew temperature). In the unheated counterfactual, 9 of 2,085 evaluated hours (0.4%), all on 9 October, fall at or marginally below the dew temperature by no more than 0.6 °C, within the equation-of-state spread reported in Section 3.6.2, so trace retrograde condensation cannot be excluded in the counterfactual for those hours, though it does not arise in operation. For computational economy the equation is solved exactly at each day’s mean operating point and at that day’s maximum-differential hour, with the integral JT coefficient interpolated linearly in pressure drop for the remaining hours. The interpolation was verified against exact solutions for 200 randomly selected hours: mean error -0.001 °C, standard deviation 0.025 °C, maximum magnitude 0.16 °C, more than an order of magnitude below the composition and instrument contributions. The effective integral JT coefficient follows as

$$\mu_{JT} = (T_{in} - T_{pred}) / (P_{in} - P_{out}) \quad (2)$$

Peng-Robinson results are cross-checked against the reference multi-fluid Helmholtz mixture formulation with GERG-2008 parameters [25], implemented in CoolProp’s HEOS backend. Both equations of state are solved exactly on the same composition and the same measured pressures and inlet temperature for a random 400-hour sample, so the reported deviation isolates the equation of state and is not contaminated by the interpolation used in the main run.

2.5 Hydrate modelling and safety margins

Hydrate-equilibrium temperature at the stream outlet pressure is estimated with the Towler–Mokhatab gas-gravity correlation [6] as the screening model, in the form $T = 13.47 \ln P + 34.27 \ln \gamma - 1.675 \ln P \ln \gamma - 20.35$, with T in °F, P the absolute outlet pressure in psia and γ the gas gravity computed from the day’s validated composition, and cross-checked with the rigorous Klauda–Sandler statistical-thermodynamic model [7] as implemented in the open-source p2f-hydratecalc package [8]. The rigorous implementation was benchmarked against the experimental natural-gas dataset distributed with the package (mean deviation +0.16 K, maximum 0.33 K) and independently against literature methane-hydrate equilibrium reference points [3]. Pentanes-plus, at no more than 0.6 mol%, are excluded from the hydrate-former slate of the rigorous model as non-formers; n-pentane and n-hexane are non-formers, while iso-pentane can stabilise structure H only in the presence of a structure-H former, none of which is present here. The exclusion applies to the rigorous model alone: the gas-gravity correlation takes the gravity of the whole gas as its only compositional input, so pentanes-plus necessarily enter it through γ . Two margins are computed for every station-hour:

$$\Delta T_{heated} = T_{out, meas} - T_{hyd}; \quad \Delta T_{unheated} = T_{pred} - T_{hyd} \quad (3)$$

The heated margin describes the station as operated; the unheated margin quantifies the counterfactual exposure that would result if the preheating contribution were removed. Throughout this paper these quantities describe thermodynamic hydrate-equilibrium exposure (that is, whether hydrate is the

thermodynamically stable phase) and not hydrate formation. Thermodynamic stability is necessary but not sufficient for formation, which additionally requires a suitable water phase together with nucleation and growth. No hydrate detection was available at this station and no claim about actual formation is made.

2.6 Preheat duty and energy comparison

The implied thermal duty delivered to the stream, and the minimum duty required to maintain a specified safety margin ΔT_{safe} , are

$$Q_{implied} = \dot{m} \bar{c}_p (T_{out, meas} - T_{pred}); \quad Q_{min} = \dot{m} \bar{c}_p \max[0, (T_{hyd} + \Delta T_{safe}) - T_{pred}] \quad (4)$$

with mass flow from the logged standard flow and daily molar mass, and mean heat capacity from the equation-of-state model. The heat capacity is the mass-basis isobaric value evaluated at the outlet pressure and the predicted unheated outlet temperature of the day's mean operating point, which varies by under 2% across a day's temperature range. Because the letdown is isenthalpic, the enthalpy difference evaluated at outlet pressure equals the duty added upstream at inlet pressure, so no separate inlet-side evaluation is required. Standard volumes are converted at the ideal-gas molar volume for 15 °C and 101.325 kPa; were the meter referenced instead to 60 °F and 14.696 psia, the duty would change by about 0.2%, and the ideal-gas assumption contributes a further 0.25%. Both are negligible against the excess reported here, and neither affects the temperature-based margins at all. The base-case safety margin is +5 °C, with +3 and +10 °C examined in sensitivity analysis. The difference between implied and minimum duty is interpreted specifically as excess thermal duty relative to the study stream's calculated requirement. It is not treated as a measurement of station-wide fuel waste, because the heater serves multiple streams on a common header and no per-stream heater efficiency is computed.

2.7 Heater-side and fuel-side verification

Two checks are applied to the reconstructed duty, and they differ in their independence. The first recomputes the duty from the measured heater outlet temperature for hours in which that record is complete. This constitutes an independent thermal measurement pathway with a shared flow basis: the two estimates use different temperature instruments but the same logged standard flow, so a systematic flow-measurement error would displace both together. The accumulator-consistency check of Section 2.3 constrains but does not eliminate this possibility. The second check uses the station fuel-skid flowmeter converted to thermal input with the measured heating value (period mean 1,128 Btu scf⁻¹ on a gross, or higher, heating-value basis, agreeing to within 0.3% with the value recomputed from the mean validated composition; the conversion efficiencies assumed in Section 4.4 are referenced to the same gross basis); because that meter serves the common header, it is used to evaluate aggregate firing behaviour rather than to assign fuel consumption to the study stream. The association between hourly fuel flow and the calculated stream demand is evaluated by correlation.

2.8 Forward validation of the reconstruction

The heater outlet temperature is the regulator inlet temperature. For every hour in which that sensor was logged, Equation (1) can therefore be solved forward on the heated path,

$$h(P_{in}, T_{heater, out}) = h(P_{out}, T_{out, pred}) \quad (5)$$

and the prediction compared against the independently measured outlet temperature. This is a true measured-versus-predicted validation: prediction and observation derive from two different temperature instruments, nothing is fitted to the outlet temperature, and, unlike the duty check of Section 2.7, no flow measurement enters at all, so the validation is fully independent of the flow basis. Equation (5) is solved exactly rather than with the coefficient of Equation (2), because μ_{JT} falls as inlet temperature rises and the coefficient obtained on the unheated path cannot be reused on the heated path.

Validation is completed by a naturally occurring high-differential excursion on 16-17 August 2025, during which the pressure differential rose from 30.5 to 44.3 bar. Because the heater outlet temperature was not

recorded on those days, the excursion tests the modelled sensitivity of outlet temperature to pressure differential rather than supplying absolute error statistics.

2.9 Uncertainty and sensitivity analysis

Five sources are examined. Composition variability is evaluated by re-running the full pipeline with the leanest and richest cross-validated daily compositions, and by re-running it under five alternative rules for handling the internally inconsistent records. Safety-margin sensitivity is evaluated at +3, +5 and +10 °C. Instrument uncertainty is propagated from assumed accuracies of ± 0.10 bar and ± 0.30 °C, pending calibration certificates, by first-order propagation and a 10,000-draw Monte Carlo analysis. Model-form sensitivity is assessed by comparing Peng-Robinson with GERG-2008 and the gas-gravity correlation with the Klauda-Sandler model. Finally, the systematic bias revealed by the forward validation is propagated to the headline hydrate-exposure figure.

2.10 Reproducibility and data governance

The analysis pipeline is scripted in Python using pandas, CoolProp 8.0.0 and matplotlib, and is re-runnable from the archived raw data. Station identity, location, document numbers and instrument tags are anonymised under the applicable data-use agreement, and operator initials and signatures were removed at ingestion.

3 Results

Section 3.1 reports data quality, which is a precondition rather than an answer to a research question. Sections 3.2 to 3.6 answer RQ1 to RQ5 in turn.

3.1 Data quality

Coverage exceeded 99.9% for pressure and temperature channels. Confirmed transcription errors were flagged and excluded, while a cluster of high inlet-pressure readings on 16-17 August, initially flagged by

the outlier screen, was verified as genuine operation and retained; it is analysed in Section 3.3.1. The composition cross-validation identified 19 of 91 daily records as internally inconsistent (Table 2), of which the two n-pentane transcription errors would have materially distorted the calculated hydrate temperature had they been used unchecked.

Two completeness findings are themselves notable given the safety-critical role of the heater. The heater outlet temperature was recorded in only 32% of hours overall, and the monthly pattern is uneven: 13% in August, 82% in September and 5% in October. The record is absent entirely on 15, 16 and 17 August, which is why the high-differential excursion cannot supply absolute validation statistics. The heater log was also outside the screening procedure applied to the operator log and contains at least two transcription errors readings of 4.01 °C and 381.70 °C against a working range of 37–40 °C, which were removed by a physical-range screen before use. The fuel flowmeter record, by contrast, is near-complete at 2,181 of 2,184 hours.

3.2 Joule-Thomson cooling behaviour (RQ1)

Across 2,157 hours at a mean pressure differential of 28.9 bar (range 17.3–44.3), the effective JT coefficient averaged 0.561 °C bar⁻¹ with an hourly range of 0.529–0.587 and a monthly range of 0.552–0.568 (Table 3). The cooling scales linearly with differential across the full operating envelope (Fig. 2a) and the effective coefficient shows no drift with operating condition (Fig. 2b). The value is consistent with published figures for lean natural gas [1, 2].

Without preheating the predicted outlet temperature would have averaged 7.2 °C, with a minimum of 0.5 °C, against measured preheated outlet temperatures averaging 25.5 °C. The preheater therefore raised the outlet temperature by 18.4 °C on average.

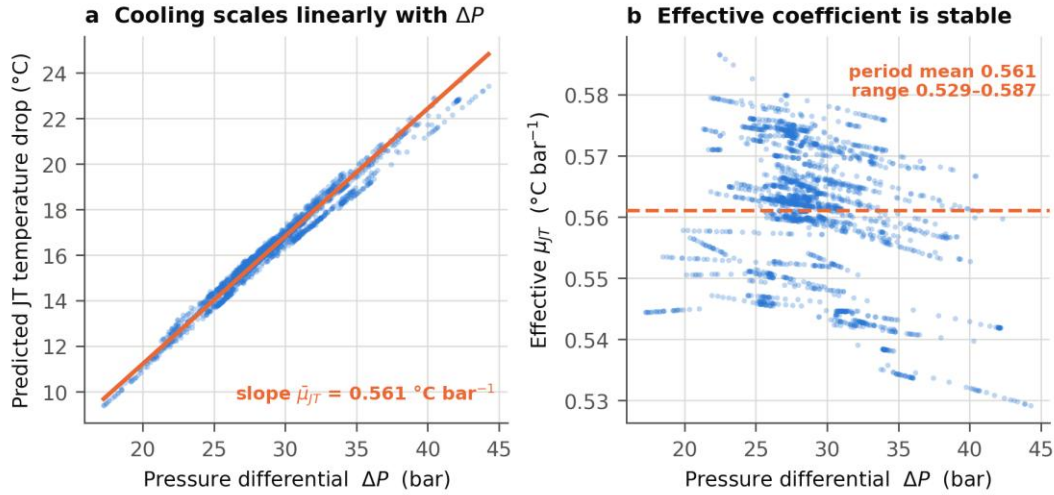


Fig. 2 Joule–Thomson characterisation over 2,157 station-hours. (a) Predicted temperature drop against pressure differential, with the period-mean coefficient. (b) Effective coefficient against pressure differential.

Table 3 Monthly Joule–Thomson and hydrate-margin summary (gas-gravity correlation basis)

Period	n (h)	μ_{JT} ($^{\circ}\text{C bar}^{-1}$)	Mean ΔP (bar)	Mean T_{pred} ($^{\circ}\text{C}$)	Heated margin mean (min) $^{\circ}\text{C}$	Unheated margin mean (min) $^{\circ}\text{C}$	Hours in hydrate region
August	736	0.552	29.9	7.7	13.5 (1.6)	-4.3 (-10.2)	96%
September	692	0.568	27.7	7.3	14.0 (9.7)	-4.8 (-9.8)	99%
October	729	0.564	29.2	6.6	12.9 (1.3)	-5.5 (-11.6)	100%
Overall	2,157	0.561	28.9	7.2	13.5 (1.3)	-4.9 (-11.6)	98%

3.3 Hydrate-equilibrium exposure (RQ2)

The hydrate-equilibrium temperature at outlet pressure averaged 12.1°C on the gas-gravity correlation basis. As operated, the heated margin averaged 13.5°C and never became negative, with a minimum of $+1.3^{\circ}\text{C}$; it fell below the $+5^{\circ}\text{C}$ design threshold in 11 hours (0.5%), every one of them between 18:00 and 05:00. In the counterfactual without preheating the stream would have lain within the calculated hydrate stability region in 98.1% of hours, with a mean margin of -4.9°C and a worst case of -11.6°C , rising from 96% of hours in August to 100% in October (Table 3, Fig. 3).

Preheating at this stream is therefore not a comfort margin but the sole barrier acting at the letdown point against routine hydrate-forming conditions, with a direct implication for heater reliability: at typical loads

a heater trip would place the stream inside the calculated stability region within the hour. As Section 2.5 states, this establishes thermodynamic stability rather than formation. Preheating is not, however, the only barrier in the system: upstream dehydration acts on water availability rather than on temperature, and is quantified in Section 3.6.5 and discussed in Section 4.3.

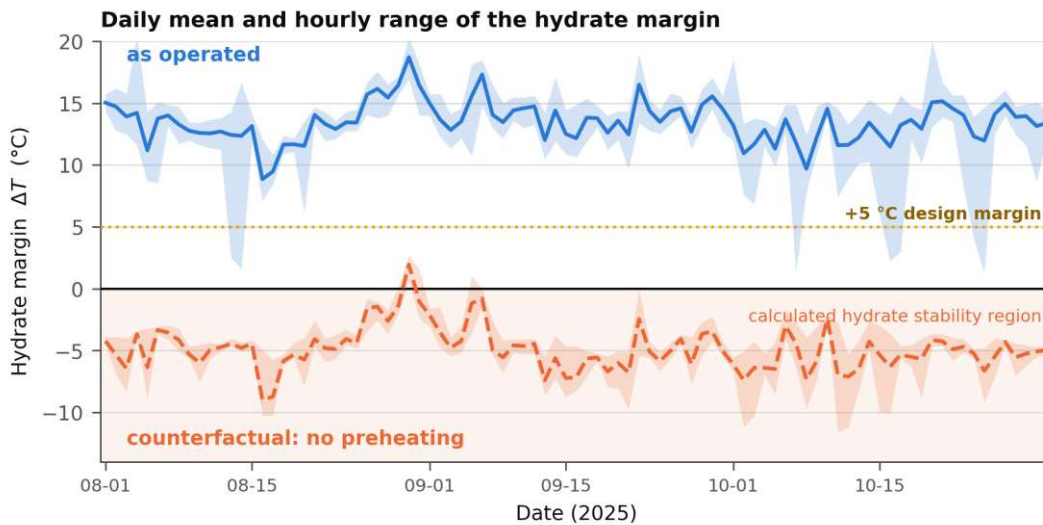


Fig. 3 Daily mean and hourly range of the hydrate margin, as operated and in the no-preheating counterfactual. The shaded band below zero is the calculated hydrate stability region.

3.3.1 The 16–17 August high-differential excursion

On 16–17 August 2025 inlet pressure rose from 66 to 79.9 barg, taking the differential from 30.5 to a period maximum of 44.3 bar at 14:00 on 17 August (Fig. 4a). The predicted unheated outlet temperature fell to 1.5 °C, a counterfactual margin of -10.3 °C, while the measured outlet temperature declined by 4.96 °C and the heated margin compressed to a minimum of +7.1 °C (Fig. 4b).

Regressing measured outlet temperature on differential while controlling for inlet temperature gives a measured sensitivity of -0.341 °C bar⁻¹, against a modelled heated-path coefficient of -0.506 °C bar⁻¹. The measured response is thus 67% of the modelled response. This is a lower bound rather than a contradiction: any heater response during the excursion would have partly offset the measured decline, and the heater record that would resolve it is absent for these days (Section 3.1). The event confirms the direction and

order of magnitude of the reconstructed behaviour, and shows operationally that the heating regime tolerated a 44-bar differential with a reduced but positive margin.

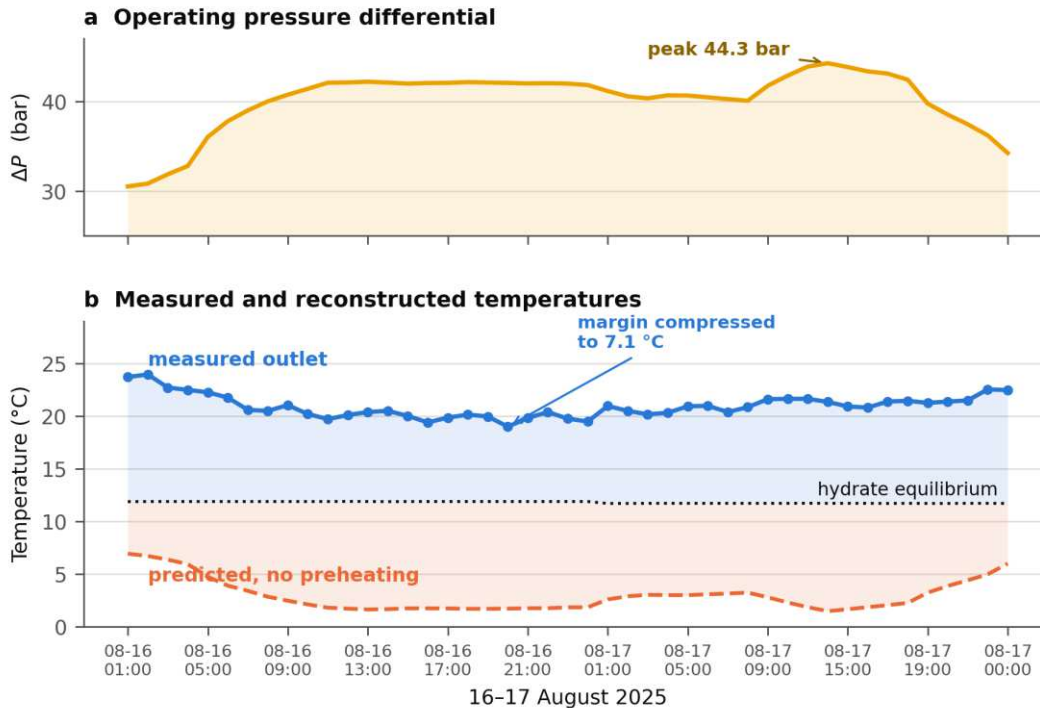


Fig. 4 The 16–17 August 2025 high-differential excursion. (a) Pressure differential. (b) Measured outlet temperature, reconstructed no-preheating temperature and hydrate-equilibrium temperature.

3.4 Delivered against required thermal duty (RQ3)

The implied duty averaged 0.89 MW against a minimum of 0.48 MW at the +5 $^{\circ}\text{C}$ margin representing an average excess of 0.41 MW, or 85%, amounting to 883 MWh of excess thermal duty relative to the study stream's calculated minimum requirement over the study period (Table 4, Fig. 5). The excess is not seasonal: delivered duty exceeded required duty in 2,142 of 2,153 hours (Fig. 6a).

The reconstruction is corroborated on the heater side. Over the 699 hours with a valid heater outlet temperature, the duty recomputed from that measurement averages 0.78 MW against 0.97 MW implied downstream for the same hours, an agreement within about 20%. As Section 2.7 notes, these two estimates constitute an independent thermal measurement pathway with a shared flow basis, and are therefore a partial

rather than a fully independent verification. Because the discrepancy is systematic, it is propagated rather than set aside: on the heater-side basis the mean delivered duty becomes 0.72 MW, the excess over the +5 °C requirement 49% rather than 85%, and the period excess approximately 510 MWh rather than 883 MWh. The defensible range for the excess is therefore 49–85%, or 510–883 MWh, with the downstream-implied figure as the upper bound.

Table 4 Monthly implied and minimum preheat duty

Period	n (h)	Implied duty mean (MW)	Minimum duty at +5 °C (MW)	Mean excess (MW)	Excess (%)	Period excess (MWh)
August	733	0.80	0.42	0.38	89	278
September	691	0.96	0.50	0.46	92	318
October	729	0.91	0.52	0.39	76	286
Overall	2,153	0.89	0.48	0.41	85	883

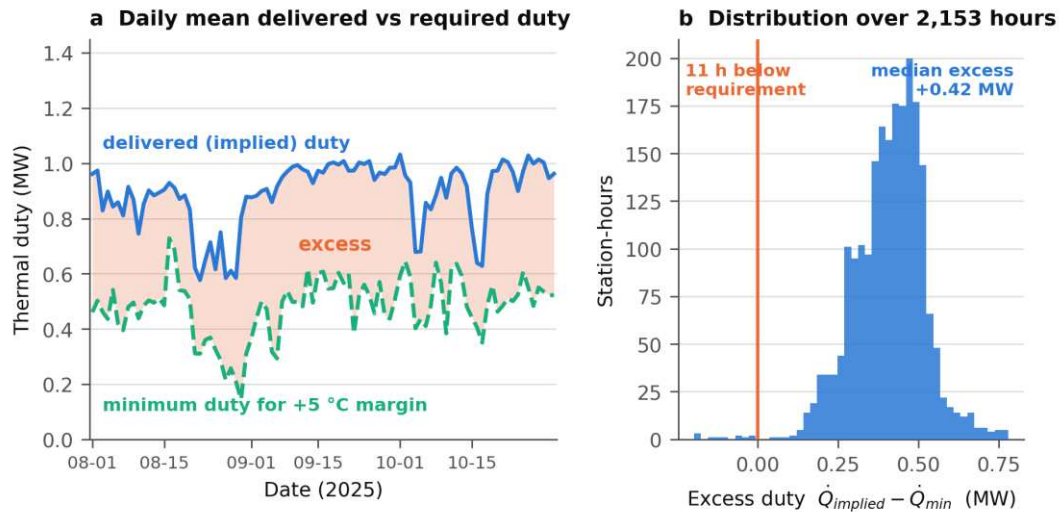


Fig. 5 (a) Daily mean delivered and minimum required duty, with the excess shaded. (b) Distribution of hourly excess over 2,153 station-hours.

3.5 Heater firing and stream demand (RQ4)

Metered fuel flow averaged 300 m³ h⁻¹, equivalent to 3.50 MW of thermal input and 23.1 MMscf over the study period, but supports all streams on the common header. The hour-by-hour correlation between fuel flow and the study stream's thermal demand is effectively zero: $r = 0.05$ against implied duty and $r = 0.04$

against minimum required duty ($n = 2,150$). Over the same period the bath temperature held at 59.6 ± 1.7 °C.

The consequence is visible in Fig. 6. Delivered duty and required duty are only weakly associated ($r = 0.64$), and the 11 low-margin hours are not hours of exceptional demand. On those hours the stream's requirement was 0.483 MW against a period mean of 0.480 MW, and flow was 77.4 MMscfd against a period mean of 78.2 MMscfd, both unremarkable. What distinguishes them is that delivered duty had collapsed to 0.379 MW against a period mean of 0.890 MW. The header did not fail to keep pace with a demand spike; it intermittently ceased to deliver while demand was ordinary.

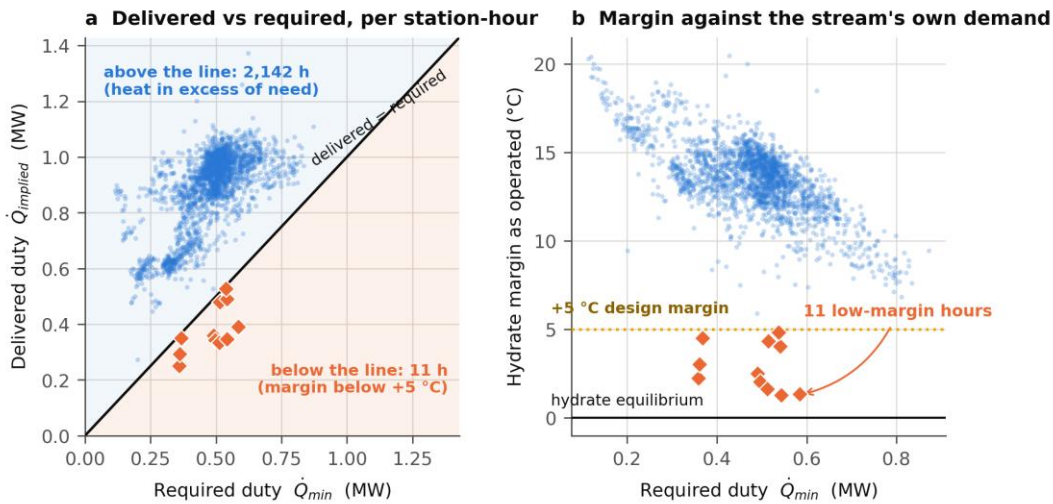


Fig. 6 (a) Delivered against required duty per station-hour; points above the diagonal received heat in excess of requirement. (b) Hydrate margin against the stream's own demand. The 11 low-margin hours are marked.

3.6 Validation, sensitivity and uncertainty (RQ5)

3.6.1 Forward validation

Over the 700 hours with a valid regulator-inlet temperature, the isenthalpic model solved forward on the heated path reproduces the independently measured outlet temperature with a mean bias of -2.15 °C, mean absolute error 2.17 °C, root-mean-square error 2.30 °C and a deviation standard deviation of 0.81 °C (Table 5, Fig. 7). The combination of a tight scatter with a systematic offset indicates that the isenthalpic form is

correct and that the discrepancy is systematic: the model tracks hour-to-hour variation while sitting uniformly cold.

The offset is not ambient heat pickup, which would scale inversely with mass flow. The residual is flow-independent ($r = 0.02$; quartile means of 4.12, 3.92, 3.90 and 3.76 °C across a 1.8-fold range of flow). The most plausible remaining explanations are a pressure drop across the heater coil, so that the differential seen by the regulator is smaller than the differential measured at the station boundary, or an offset in one of the two temperature instruments. These cannot be separated with the available instrumentation. The direction of the bias is conservative for hydrate-margin assessment: the model predicts a colder outlet than is measured.

Table 5 also reports the naïve comparison in which the unheated-path coefficient is reused on the heated path, which is why Equation (5) is solved exactly. The coefficient falls from 0.569 to 0.506 °C bar⁻¹ between the unheated (23.1 °C) and heated (38.4 °C) inlet conditions. The empirical coefficient obtained by regressing the measured drop on differential through the origin is 0.430 °C bar⁻¹.

Table 5 Forward validation of the isenthalpic model against independently measured outlet temperature (n = 700 station-hours)

Metric	Heated-path exact solve	Unheated- μ (naïve)
Mean bias, predicted – measured (°C)	-2.15	-3.93
Mean absolute error (°C)	2.17	3.93
Root-mean-square error (°C)	2.30	4.01
Standard deviation of deviation (°C)	0.81	0.81
Maximum absolute deviation (°C)	10.61	11.54
Mean measured regulator-inlet temperature (°C)	38.41	—
Mean measured outlet temperature (°C)	26.32	—
Field μ_{JT} , through-origin regression (°C bar ⁻¹)	0.430	—

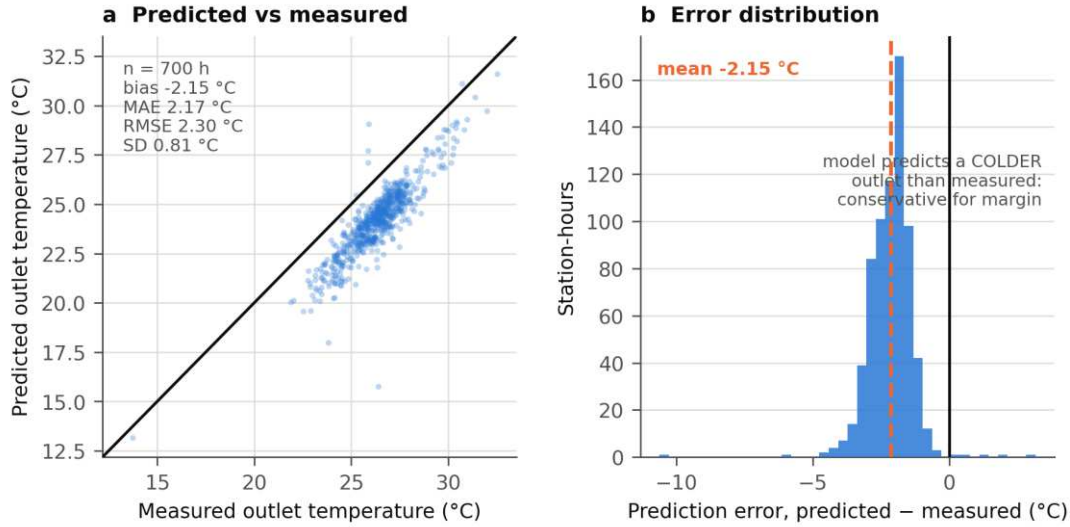


Fig. 7 Forward validation over 700 station-hours. (a) Predicted against measured outlet temperature. (b) Distribution of prediction error.

3.6.2 Equation of state

On a 400-hour sample with both equations solved exactly, Peng–Robinson predicts outlet temperatures 1.157 °C colder than the GERG-2008 reference, with mean absolute error 1.157 °C, root-mean-square error 1.163 °C, deviation standard deviation 0.114 °C and a maximum absolute deviation of 1.513 °C (Table 6). The deviation is systematic rather than scattered, grows with pressure differential (the maximum occurs at the period’s highest differential), and its sign makes Peng–Robinson the conservative choice for hydrate-margin assessment. Counterfactual exposure over the same sample is 99.0% on the Peng–Robinson basis and 98.5% on the GERG-2008 basis.

Table 6 Equation-of-state validation, Peng–Robinson against GERG-2008 (n = 400 station-hours)

Metric	Peng–Robinson	GERG-2008	Difference
Mean predicted outlet temperature (°C)	7.136	8.293	−1.157
Minimum predicted outlet temperature (°C)	1.059	2.519	−1.460
Maximum predicted outlet temperature (°C)	14.425	15.182	−0.758
Standard deviation of T_pred (°C)	1.900	1.797	+0.103
Mean effective μ_{JT} (°C bar ^{−1})	0.5612	0.5211	+0.0401
Mean absolute error (°C)	—	—	1.157

Metric	Peng–Robinson	GERG-2008	Difference
Root-mean-square error (°C)	—	—	1.163
Mean bias, PR – GERG (°C)	—	—	–1.157
Standard deviation of deviation (°C)	—	—	0.114
Maximum absolute deviation (°C)	—	—	1.513

3.6.3 Gas composition

Re-running the full pipeline with the leanest and richest cross-validated compositions (specific gravity 0.635 and 0.656) gives counterfactual exposures of 98% and 99% respectively against a base case of 98%. The rule adopted for the internally inconsistent records is likewise immaterial. Five rules were run end to end (Table 7): using each day’s own composition, the nearest preceding validated composition, the nearest validated composition in either direction, a linear interpolation of the bracketing validated compositions, and the period-mean validated composition. Hydrate exposure varies by 0.09 percentage points across all five, the period excess by 1.5 MWh out of 883, and the count of low-margin hours is 11 under every rule.

Table 7 Sensitivity of the conclusions to the gas-composition substitution rule (all 2,157 station-hours)

Composition rule	Mean SG	Hours in hydrate region (%)	Mean unheated margin (°C)	Hours below +5 °C	Period excess (MWh)
A Each day’s own composition (base case)	0.6438	98.1	–4.88	11	883
B Nearest preceding validated	0.6447	98.1	–4.94	11	881
C Nearest validated, either direction	0.6445	98.1	–4.92	11	882
D Linear interpolation of neighbours	0.6444	98.1	–4.92	11	882
E Period-mean validated composition	0.6451	98.2	–4.96	11	881
Spread across all rules	0.0013	0.09	0.08	0	1.5

3.6.4 Hydrate model, safety margin and instrument uncertainty

The Kluda–Sandler model, benchmarked to within 0.33 K of experimental data, confirms structure-II hydrates and places the hydrate temperature 1.5–1.6 °C above the gas-gravity correlation (13.7 against 12.1 °C at outlet pressure); the screening correlation is therefore non-conservative for this gas. On the rigorous basis the counterfactual exposure rises to 99%, and the two lowest heated-margin hours fall to –0.3 °C, placing them at the equilibrium threshold within model uncertainty.

Varying the design margin gives period excesses of 1,091, 883 and 361 MWh at +3, +5 and +10 °C, so the surplus persists even at the most conservative margin. Propagated instrument uncertainty on the margin is ± 0.31 °C, with first-order and Monte Carlo results agreeing, which is negligible against margins spanning -5 to $+13$ °C. Instrument scatter is not, however, the dominant uncertainty: the equation-of-state and hydrate-model contributions are several times larger, as is the forward-validation bias.

Table 8 propagates the systematic corrections to the headline exposure figure. The qualitative conclusion is unchanged across the full range: preheating remains the sole temperature-side barrier whichever combination is adopted.

Table 8 Counterfactual hydrate-equilibrium exposure under systematic model corrections (n = 2,157 station-hours)

Basis	Hours below equilibrium	Share of hours
As modelled (Peng–Robinson, gas-gravity correlation)	2,116	98.1%
+1.16 °C: Peng–Robinson to GERG-2008 shift	2,070	96.0%
+2.15 °C: forward-validation bias	1,976	91.6%
+3.31 °C: both corrections applied additively	1,824	84.6%
+3.31 °C with Klauda–Sandler hydrate model (-1.55 °C)	2,002	92.8%
Defensible range	1,824–2,116	85–98%

3.6.5 Water content

Water-vapour content was reported on 80 of the 91 days, with a median of 0.29 lb MMscf⁻¹, an interquartile range of 0.29 - 0.35 and a maximum of 1.14 lb MMscf⁻¹. Nineteen of the 80 reported values are exactly zero and are treated here as non-detections rather than true zeros. At the median loading the water dew point at outlet pressure lies approximately 49 °C below the hydrate-equilibrium temperature. This provides a thermodynamic basis for the absence of bulk liquid-water condensation under the observed conditions, while not eliminating hydrate nucleation or localised formation mechanisms, including nucleation from vapour-phase water, or condensation at cold surfaces or in stagnant legs not represented by a bulk-stream measurement. Because no hydrate detection was available, the absence of reported operational incident is consistent with, but does not demonstrate, the absence of formation.

4 Discussion

In summary, the field data establish a stable JT characterisation ($0.561\text{ }^{\circ}\text{C bar}^{-1}$), a counterfactual hydrate-equilibrium exposure of 85–98% of hours without preheating, an average over-provision of preheat of 85% relative to a $+5\text{ }^{\circ}\text{C}$ margin, 11 hours in which the margin nonetheless fell below that threshold, and firing that is uncorrelated with the study stream's thermal demand. Table 9 positions these findings against prior work.

Table 9 Comparison with prior studies of pressure-reduction station preheating

Study	Dataset	Method	Main finding	Limitation	Contribution of the present study
Deymi-Dashtebayaz et al. [17]	Operating city gate station, Iran; representative conditions	Thermodynamic optimisation of minimum regulator inlet temperature on a hydrate basis	$\approx 35\%$ fuel reduction achievable	Prescriptive optimum at representative conditions; no hour-resolved audit of realised delivery	Measures the realised gap between delivered and required duty hour by hour
Olfati et al. [18]	City gate station, 20,000 SCMH; four seasonal strategies	Energy and exergy analysis using AGA-8	Regulator is the most exergy-destructive component despite high energy efficiency; exergy loss 1.60 kW (summer) to 15.33 kW (winter)	Seasonal representative points; single fixed composition	Continuous 91-day hourly record with each day's measured composition; quantifies margin as well as efficiency
Olfati et al. [19]	Two sample stations, 10,000 SCMH; modelled	Minimum preheat temperature for hydrate avoidance, with heater disengagement above it	$\geq 33\%$ energy reduction, $\geq 15\%$ less exergy destruction, $\geq 80\%$ CO_2 reduction	Modelled intervention, not demonstrated on an operating station; single-stream	Supplies the measured demand profile such a controller must track, and shows why a common header defeats it
Ebrahimi-Moghadam et al. [13]	City gate station indirect heaters; modelled control system	Energetic, exergetic, environmental and economic assessment of online hydrate-temperature control	Online modulation of firing is economically and environmentally favourable	Assessed against modelled rather than measured operation	Provides field evidence that firing is currently uncorrelated with stream demand ($r = 0.05$)
Rastegar et al. [20]	Pressure-reduction station outlet temperature	Predictive model for outlet gas temperature	Outlet temperature is predictable well enough to reduce energy loss	Prediction only; no hydrate-margin or duty accounting; no independent in-service validation	Validates the reconstruction against an independent measured temperature pathway (bias $-2.15\text{ }^{\circ}\text{C}$, SD $0.81\text{ }^{\circ}\text{C}$, $n = 700\text{ h}$)
Deymi-Dashtebayaz et al. [9]	Review of indirect water-bath heater efficiency and replacement	Survey of improvement and replacement strategies	Indirect heaters are a persistent low-efficiency bottleneck; many technology routes exist	Addresses heater technology rather than control architecture	Identifies control architecture, not heater capacity or technology, as the binding constraint

4.1 Comparison with prior findings

Prior work on pressure-reduction station preheating divides into optimisation studies and thermodynamic characterisations. Deymi-Dashtebayaz et al. [17] established that setting the regulator inlet temperature from the hydrate boundary rather than a fixed setpoint can recover on the order of 35% of heater fuel at an operating station, and Olfati et al. [19] extended this into a demand-following control concept with modelled energy savings of at least 33% and CO₂ reductions above 80%. Both results are consistent in magnitude with the excess reported here (delivered duty exceeding the hydrate-avoidance requirement by 85% on average), but the basis differs. Those figures are optimisation outcomes computed at representative conditions; the present figure is the measured gap over 2,153 consecutive station-hours, which is what a control intervention would actually have to close.

The exergy literature locates the loss differently. Olfati et al. [18] identify the regulator as the most exergy-destructive component of a city gate station despite its high first-law efficiency, with seasonal exergy losses from 1.60 kW in summer to 15.33 kW in winter. The present study does not contradict that finding but reframes the operational question: at this station the dominant recoverable quantity is not the exergy destroyed in the regulator but the enthalpy added upstream of it and never required, 883 MWh over a single 92-day period on one stream. Where a seasonal analysis averages over the variation, an hourly reconstruction shows the excess to be present in 2,142 of 2,153 hours rather than concentrated in a season.

4.2 Interpretation: a control-architecture argument

The coexistence of chronic average over-heating with episodic under-heating is best explained by the station's heating architecture rather than by operator behaviour. The evidence supporting that reading is as follows. The study stream's thermal demand varies hour to hour, with the required duty ranging from 0.10 to 0.87 MW. Bath temperature holds near-constant at 59.6 ± 1.7 °C throughout. Metered fuel flow is uncorrelated with the stream's demand ($r = 0.05$). The heater serves a common header feeding streams of differing letdown ratio, so the setpoint must protect the most demanding stream, and a moderate-letdown stream would on that basis be over-supplied on average. This last point differs in kind from the three that precede it: it is an inference from the station's configuration rather than a measurement. The remaining

letdown streams are not separately logged, so neither the heterogeneity of demand across the header nor the identity of the most demanding stream could be established from the available records, and the argument rests on the measured behaviour of the study stream together with the configuration of the header.

The observed behaviour is therefore consistent with aggregate or common-header setpoint control rather than stream-level modulation. The station control logic was not available to the authors, and no claim is made about the implemented control algorithm; the inference is from behaviour, not from the controller.

The 11 low-margin hours sharpen this reading. Were the mechanism simply that the header cannot meet peak demand, those hours would show elevated requirement. They do not: requirement and flow are both at period-average levels, and what distinguishes them is a collapse in delivered duty from 0.890 to 0.379 MW. A control architecture that does not observe an individual stream cannot protect it, and the failure mode is not saturation but inattention. This is a stronger argument for stream-level trim control than an efficiency calculation alone, because it couples the fuel case to a safety case.

4.3 Validation and the interpretation of margin

The validation basis of this study differs from prior work. Rastegar et al. [20] develop predictive models for station outlet temperature but validate them against the same class of data to which they are fitted. The present reconstruction is confronted with an independent in-service temperature pathway, 700 hours in which the regulator inlet was separately instrumented, giving a mean bias of -2.15 °C with a deviation standard deviation of 0.81 °C. The tight scatter against a systematic offset indicates that the isenthalpic form is correct while the station-boundary differential slightly overstates the differential seen by the regulator. Reporting that offset, rather than absorbing it, is what allows the hydrate-exposure conclusion to be stated with a defensible uncertainty band of 85–98% of hours rather than a single unqualified figure.

Two implications follow for margin policy. Well-dehydrated gas provides a second, independent barrier, here quantified as a water dew point some 49 °C below the hydrate-equilibrium temperature at the median loading, and margin requirements could in principle be conditioned on measured water content rather than

applied uniformly. But dryness is itself an operational variable. The record shows a maximum loading four times the median, and an upstream dehydration upset would remove the second barrier precisely when it went unnoticed, so the thermodynamic margin should remain the design basis.

4.4 Practical and methodological relevance

Practically, the results give the operator a quantified, partially verified case for stream-level trim control. The two candidate mechanisms address different failure modes and are complementary rather than alternative. A controlled partial bypass addresses the excess, since routing part of the flow around the heater reduces delivered duty in the 2,142 hours of over-delivery; a trim heater cannot, because it can only add heat. Conversely, a downstream trim heater addresses the 11 low-margin hours, in which delivered duty had collapsed to 0.379 MW while requirement was ordinary; a bypass cannot, because the deficit is one of under-delivery. A stream-level scheme combining both would address the excess and the low-margin episodes together. Because the excess arises from the header setpoint rather than from burner behaviour, it cannot be recovered by adjusting firing. Table 10 sets out the potential fuel-cost-saving opportunity across plausible gas prices and heater conversion efficiencies. The 70-90% range adopted there is a marginal conversion efficiency at steady firing, and should not be confused with the sub-40% seasonal figures cited in Section 1, which are annualised values that include standby, cycling and shutdown losses. Were the station's marginal efficiency closer to those seasonal figures, the opportunity would be correspondingly larger. The central case is approximately US\$121,000 per year, with a range of US\$67,000 to US\$207,000 depending on assumptions. These are potential opportunities rather than guaranteed savings: they are conditional on the excess being recoverable by stream-level control, on the assumed heater conversion, on the assumed gas price, and on the study period being representative of the year.

Any such scheme would require a safety and control assessment before implementation, which is beyond the scope of this study but whose principal questions follow from the results reported here. A controlled bypass deliberately reduces the barrier that Section 3.3 identifies as the only one acting at the letdown point, so the failure mode of a bypass valve held open, and the means and speed of its detection, must be

established against the finding that a loss of preheat would place the stream inside the calculated stability region within the hour. Blend-temperature control is hardest at low flow, and the low-margin hours identified here are overnight hours; the proposed control would therefore have to perform in precisely the conditions in which it is least favoured. The streams are also coupled through the shared bath, so bypassing one stream alters bath load and hence the inlet temperature of the others, and a per-stream intervention is not a local change. Finally, a margin-tracking controller requires an online hydrate-equilibrium computation and therefore online composition, whereas composition at this station is available daily and, as Section 2.3 shows, failed internal validation in 19 of 91 records.

Table 10 Potential annual fuel-cost-saving opportunity for the study stream (US\$ per year, 365/92 scaling of the measured 883 MWh excess)

Heater conversion efficiency	US\$5/MMBtu	US\$8/MMBtu	US\$12/MMBtu
70%	86,300	138,000	207,100
80% (base case)	75,500	120,800	181,200
90%	67,100	107,400	161,100

At the base-case assumptions the equivalent figures for the +3 and +10 °C safety margins are approximately US\$149,000 and US\$49,000 per year. The annualisation is a linear extrapolation of a single 92-day period spanning one seasonal transition, and should be read as a notional rate rather than a measured annual quantity.

Methodologically, the study shows that the records most stations already keep (hourly shift logs and daily gas-quality reports) can support an analysis of this kind after structured quality screening, using only open-source tools. The screening is not optional: the composition cross-validation caught two transcription errors that would otherwise have distorted the calculated hydrate temperature, and the heater log, which lay outside the original screening scope, proved to contain errors of its own. That the heater outlet temperature was recorded in only a third of hours, and not at all during the period's largest differential, is itself an argument for basic digital data acquisition at manned stations.

4.5 Limitations and future research

548 The following limitations bound the interpretation of these results.

549 • Scope. The study covers one stream at one station over 91 days spanning a single seasonal transition.

550 The mechanism described may be applicable to comparable multi-stream stations using common-

551 header preheating, but broader validation across stations, streams and seasons is required before it can

552 be treated as general.

553 • No hydrate detection. Formation is inferred thermodynamically only; no measurement of nucleation,

554 deposition or blockage was available.

555 • Temporal resolution. Hourly manual readings cannot resolve sub-hourly transients, and excursions

556 shorter than the logging interval are invisible.

557 • Composition resolution. Gas composition is available daily rather than hourly.

558 • Fuel metering and stream coverage. Metering is station-level on a common header, and the remaining

559 letdown streams carry no separate operator log, so no stream-specific fuel consumption or heater

560 efficiency can be computed and the heterogeneity of demand across the header cannot be evidenced.

561 Closing a header energy balance, which would yield the heater's field efficiency directly and replace

562 the assumed conversion of Table 10, requires instrumentation the station does not presently carry.

563 • No intervention test. The proposed stream-level trim control is evaluated against reconstructed

564 demand profiles and has not been implemented or tested.

565 • Instrument accuracy. Accuracies were assumed pending calibration certificates.

566 • Validation coverage. The regulator-inlet temperature was logged in 32% of hours, unevenly across

567 months, and not at all during the highest-differential period, so the forward validation does not cover

568 the most demanding conditions.

569 • Unresolved bias. The $-2.15\text{ }^{\circ}\text{C}$ forward-validation bias cannot be attributed between heater-coil

570 pressure drop and instrument offset with the available instrumentation.

Future work should instrument and log the remaining letdown streams so that the reconstruction can be extended across the whole header, the shared-header trade-off quantified, the heater's field efficiency obtained from a closed energy balance, and any stream whose margin the common setpoint leaves thin identified; extend the record to a full annual cycle; instrument the regulator inlet continuously so that the forward validation can cover the full operating envelope; measure the heater-coil pressure drop to resolve the systematic bias; and evaluate stream-level trim control and margin-tracking heater strategies against the demand profiles developed here.

5 Conclusions

From 2,157 field-recorded station-hours at an operating West African pressure-regulating station, five findings follow.

1. Joule-Thomson cooling at this stream is stable and measurable. The effective coefficient is $0.561\text{ }^{\circ}\text{C}\cdot\text{bar}^{-1}$, varying by less than 3% between months, and it is corroborated by a reference equation of state and by a 44-bar in-service excursion.
2. Preheating is essential for thermodynamic hydrate protection, not a comfort margin. Without it the stream would have lain within the calculated hydrate stability region in 98% of hours on the as-modelled basis and in 85-98% of hours across the full range of model corrections. Preheating is the sole barrier acting at the letdown point; upstream dehydration provides a second barrier acting on water availability, but it is neither measured continuously nor under the station's control.
3. The current architecture provides excess thermal duty on average. Delivered duty exceeded the $+5\text{ }^{\circ}\text{C}$ -margin requirement by 85%, amounting to 883 MWh of excess thermal duty relative to the stream's calculated minimum requirement over a single 92-day period, in 2,142 of 2,153 hours. On the heater-side duty basis the corresponding figures are 49% and 510 MWh; the defensible range is 49–85%.

4. Low-margin periods nonetheless remain. In 11 hours, all overnight, the margin fell below the +5 °C design threshold. These are not high-demand hours: requirement and flow were at period-average levels and delivered duty had collapsed to 0.379 MW against a period mean of 0.890 MW.

5. The issue is therefore control architecture, not heater capacity. Fuel firing is uncorrelated with the stream's thermal demand ($r = 0.05$) while bath temperature holds near 59.6 °C, behaviour consistent with aggregate control of a common header serving heterogeneous letdown streams, which can produce over-provision and residual vulnerability simultaneously.

Stream-level trim control should be evaluated for this station, combining a controlled partial bypass to address the excess with a trim heater to address the low-margin hours. Because the excess originates in the header setpoint rather than in burner behaviour, adjusting firing cannot recover it, and because the low-margin hours arise from unobserved delivery rather than saturated capacity, added capacity would not prevent them. A margin-based control strategy that observes each stream would address the fuel and the safety case together.

The reconstruction should be extended across all streams of a multi-stream station, over a full annual cycle, and at sub-hourly resolution, with the regulator inlet continuously instrumented so that the forward validation covers the full operating envelope. Operators of comparable stations may find the audit-and-reconstruct methodology applicable to their own shift records before investing in new instrumentation, and the data-quality findings reported here may support minimum digital-acquisition requirements at manned letdown stations.

List of abbreviations

CGS: city gate station

GC: gas chromatograph

GERG-2008: Groupe Européen de Recherches Gazières 2008 equation of state

617 JT: Joule–Thomson
618 MAD: median absolute deviation
619 MMscfd: million standard cubic feet per day
620 MW: megawatt
621 MWh: megawatt hour
622 PR: Peng–Robinson equation of state
623 RQ: research question
624 SG: specific gravity

625 **Declarations**

626 **Availability of data and materials**

627 The operating data underlying this study were obtained from the station operator under a confidentiality
628 agreement and cannot be openly deposited. They are available from the corresponding author on reasonable
629 request, subject to the operator’s approval. The analysis scripts, which reproduce every reported quantity
630 from the archived raw data, are openly available under the MIT Licence at
631 <https://doi.org/10.5281/zenodo.22499288>. They are written in Python and pinned to CoolProp 8.0.0, as
632 mixture equation-of-state output is version-sensitive. A de-identified derived dataset sufficient to reproduce
633 every reported figure and table, covering hourly pressure differential, reconstructed and measured
634 temperatures, hydrate margins and duties, may be added to the same record if the operator approves its
635 release.

636 **Competing interests**

637 One of the authors, VNA, is employed by the operator of the station studied. The remaining authors declare
638 no competing financial interests or personal relationships that could have appeared to influence the work
639 reported in this paper. The operator is not named because access to the operational records was granted

under a written data-use agreement specifying anonymisation of the station identity, location, document numbers and instrument tags. That agreement grants the operator review of the manuscript for residual identifying detail only, with no influence over the analysis, findings, conclusions, or the decision to publish. The thermodynamic reconstruction, the analysis and the interpretation reported here were carried out independently of the operator by the corresponding author.

Funding

This research received no specific grant from funding agencies in the public, commercial or not-for-profit sectors

Authors' contributions

Conceptualization, FBAA; methodology, FBAA, OKD and TFA; software, FBAA; validation, FBAA; formal analysis, FBAA and TFA; investigation, FBAA and VNA; resources, VNA; data curation, FBAA; writing – original draft preparation, FBAA; writing – review and editing, OKD, VNA and TFA; visualization, FBAA. All authors read and approved the final manuscript.

Acknowledgements

The authors thank the station operator for access to the operational records under a data-use agreement.

Ethics approval and consent to participate

Not applicable. No human participants, human data or human tissue were involved. Operator initials and signatures present in the source records were removed at data ingestion. Consent for publication: not applicable; the manuscript contains no individual person's data in any form.

References

1. Mokhatab S, Poe WA, Mak JY (2018) Handbook of natural gas transmission and processing: principles and practices, 4th edn. Gulf Professional Publishing, Cambridge
2. Li J, Su Y, Yu B, Wang P, Sun D (2021) Influences of hydrogen blending on the Joule–Thomson coefficient of natural gas. *ACS Omega* 6(26):16722–16735
3. Sloan ED, Koh CA (2008) Clathrate hydrates of natural gases, 3rd edn. CRC Press, Boca Raton
4. Jeong K, Norris BW, May EF, Aman ZM (2023) Hydrate formation from Joule–Thomson expansion using a single pass flowloop. *Energies* 16(22):7594. <https://doi.org/10.3390/en16227594>
5. Jeong K, Norris BW, Siahvashi A, Jiao F, Patterson JE, Estanga D, May EF, Aman ZM (2024) A Joule–Thomson loop to study high-pressure fluid expansion. *Energy Fuels* 38(21):21651–21660. <https://doi.org/10.1021/acs.energyfuels.4c02784>
6. Towler BF, Mokhatab S (2005) Quickly estimate hydrate formation conditions in natural gases. *Hydrocarb Process* 84(4):61–63
7. Klauda JB, Sandler SI (2003) Phase behavior of clathrate hydrates: a model for single and multiple gas component hydrates. *Chem Eng Sci* 58(1):27–41. [https://doi.org/10.1016/S0009-2509\(02\)00435-9](https://doi.org/10.1016/S0009-2509(02)00435-9)
8. Kunneman K, Sum AK (2025) p2f-hydratecalc: a web Python-based tool for the prediction of natural gas hydrate equilibrium and inhibition. *SoftwareX* 32:102422. <https://doi.org/10.1016/j.softx.2025.102422>
9. Deymi-Dashtebayaz M, Mirzadeh-Sijavandi M, Soleymani E, Hosseinzadeh D, Ghorbani S, Tian Z (2026) Review of strategies to improve the efficiency and replace of indirect water bath heaters in city gate stations. *Renew Sustain Energy Rev* 225:116158. <https://doi.org/10.1016/j.rser.2025.116158>
10. Mostafavi SA, Shirazi M (2020) Thermal modeling of indirect water heater in city gate station of natural gas to evaluate efficiency and fuel consumption. *Energy* 212:118390. <https://doi.org/10.1016/j.energy.2020.118390>
11. Delouei AA, Naeimi H, Sajjadi H, Atashafrooz M, Imanparast M, Chamkha AJ (2024) An active approach to heat transfer enhancement in indirect heaters of city gate stations: an experimental modeling. *Appl Therm Eng* 237:121795

12. Ashouri E, Veysi F, Shojaeizadeh E, Asadi M (2014) The minimum gas temperature at the inlet of regulators in natural gas pressure reduction stations (CGS) for energy saving in water bath heaters. *J Nat Gas Sci Eng* 21:230–240
13. Ebrahimi-Moghadam A, Deymi-Dashtebayaz M, Jafari H, Niazmand A (2020) Energetic, exergetic, environmental and economic assessment of a novel control system for indirect heaters in natural gas city gate stations. *J Therm Anal Calorim* 141(6):2573–2588. <https://doi.org/10.1007/s10973-020-09413-4>
14. Farzaneh-Gord M, Ghezelbash R, Arabkoohsar A, Pilevari L, Machado L, Koury RNN (2015) Employing geothermal heat exchanger in natural gas pressure drop station in order to decrease fuel consumption. *Energy* 83:164–176. <https://doi.org/10.1016/j.energy.2015.02.093>
15. Cheli L, Meazzini M, Busi L, Carcasci C (2023) Integration of renewable energy systems at city gate stations to reduce pre-heating gas consumption. *J Sustain Dev Energy Water Environ Syst* 11(3):1–21
16. Neseli MA, Ozgener O, Ozgener L (2015) Energy and exergy analysis of electricity generation from natural gas pressure reducing stations. *Energy Convers Manag* 93:109–120. <https://doi.org/10.1016/j.enconman.2015.01.011>
17. Deymi-Dashtebayaz M, Khorsand M, Rahbari HR (2019) Optimization of fuel consumption in natural gas city gate station based on gas hydrate temperature (case study: Abbas Abad station). *Energy Environ* 30(3):408–426. <https://doi.org/10.1177/0958305X18793107>
18. Olfati M, Bahiraei M, Heidari S, Veysi F (2018) A comprehensive analysis of energy and exergy characteristics for a natural gas city gate station considering seasonal variations. *Energy* 155:721–733. <https://doi.org/10.1016/j.energy.2018.05.069>
19. Olfati M, Bahiraei M, Veysi F (2019) A novel modification on preheating process of natural gas in pressure reduction stations to improve energy consumption, exergy destruction and CO₂ emission: preheating based on real demand. *Energy* 173:598–609. <https://doi.org/10.1016/j.energy.2019.02.090>
20. Rastegar S, Kargarsharifabad H, Khalesi Doost A, Rahbar N (2020) Developing a model for predicting the outlet gas temperature of natural gas pressure reduction stations to reduce energy loss. *J Heat Mass Transf Res* 7(2):143–154

- 711 21. Chao AC (2016) Anomaly detection for natural gas regulator stations. MSc thesis, Massachusetts Institute of
712 Technology, Cambridge
- 713 22. Obanijesu EO, Macaulay SRA (2009) West African Gas Pipeline (WAGP) project: associated problems and
714 possible remedies. In: Yanful EK (ed) Appropriate technologies for environmental protection in the developing
715 world. Springer, Dordrecht, pp 101–112. https://doi.org/10.1007/978-1-4020-9139-1_12
- 716 23. Peng DY, Robinson DB (1976) A new two-constant equation of state. *Ind Eng Chem Fundam* 15(1):59–64.
717 <https://doi.org/10.1021/i160057a011>
- 718 24. Bell IH, Wronski J, Quoilin S, Lemort V (2014) Pure and pseudo-pure fluid thermophysical property evaluation
719 and the open-source thermophysical property library CoolProp. *Ind Eng Chem Res* 53(6):2498–2508.
720 <https://doi.org/10.1021/ie4033999>
- 721 25. Kunz O, Wagner W (2012) The GERG-2008 wide-range equation of state for natural gases and other mixtures:
722 an expansion of GERG-2004. *J Chem Eng Data* 57(11):3032–3091. <https://doi.org/10.1021/je300655b>