

Experimental Investigation of Joule-Thomson Cooling Induced by Welded Joint Geometry in Natural Gas Pipelines

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Abstract

The Joule–Thomson (JT) effect is well characterized at engineered throttling devices such as valves, regulators, and leak orifices, but its occurrence at internal weld-joint geometry, an unintentional, workmanship-tolerance-scale feature present at every girth weld, has not previously been established experimentally; existing JT-cooling studies assume an intentional, externally specified throttling geometry, while weld-integrity studies address the erosion, corrosion, and stress consequences of internal weld irregularities without examining their thermal effect. This study addresses that gap by providing controlled experimental evidence of weld-induced JT cooling as a distinct micro-throttling mechanism. The objective was to determine whether internal weld-joint geometry (weld reinforcement and hi-lo misalignment) constitutes a measurable, thermodynamically consistent JT throttling mechanism under representative natural gas transmission conditions. A natural gas pipeline test section incorporating a smooth-pipe baseline and four internal weld geometries (low, medium, and high reinforcement, and hi-lo misalignment) was tested at upstream pressures of 40–70 bar and flow velocities of 5–15 m/s, with the measured response validated against Peng-Robinson-based isenthalpic predictions ($\Delta T = \mu_{JT} \Delta P_w$) and independent CFD simulation. The CFD simulation reproduced the experimental pressure loss to within an average of 3.5%. Weld-induced pressure loss and the corresponding corrected temperature response increased systematically with geometric severity and flow velocity, reaching a maximum additional pressure loss of 0.199 bar and a maximum corrected temperature reduction of 0.0404 K for the hi-lo geometry at 60 bar and 15 m/s; flow velocity accounted for 55.96% of the variance in the response, followed by weld geometry (26.62%) and their interaction (13.84%), and a regression model linking temperature response to weld severity, velocity, and pressure achieved $R^2 = 0.9642$. These results confirm that internal weld geometry constitutes a genuine, thermodynamically consistent local JT throttling mechanism, one that is two to three orders of magnitude smaller than the cooling associated with engineered throttling devices and unlikely to present a significant hydrate, embrittlement, or corrosion hazard at an isolated girth weld.

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Keywords: Joule–Thomson effect; Girth weld; Natural gas pipeline; Micro throttling; Thermodynamic modelling

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1. Introduction

The Joule–Thomson (JT) effect, an isenthalpic temperature change accompanying the throttling of a real gas from higher to lower pressure, is central to the design, operation, and integrity monitoring of natural gas transmission systems [1]. Because natural gas is in its positive

JT inversion region at typical transmission pressures, pressure drop along the line produces detectable cooling that influences pressure-letdown station sizing, hydrate-formation and low-temperature-embrittlement assessments, and fiber-optic leak-detection interpretation [2]. This significance extends to oil and gas well testing, drilling, completion, and production monitoring, where JT-linked hydrate formation is a persistent operational challenge [3,4], and parallels comparable thermal-hydraulic coupling reported

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in heat-exchanger and process-unit studies, where local flow and geometric conditions similarly govern temperature response [5,6].

A substantial body of work has focused on improving equation-of-state predictions of the JT coefficient for purposefully engineered throttling geometries, spanning natural-gas flow-measurement correction, hydrogen-refuelling and fuel-cell circulation safety, and CO₂-N₂ mixtures relevant to carbon capture and storage [1,7,8], as well as SAFT-, cubic-, and CPA-type equations of state benchmarked against pure-component and natural-gas JT coefficients and inversion curves, and CFD-based reproduction of the JT-valve process itself [29–34]. In every case, however, the throttling feature examined valve, regulator, orifice, or engineered restriction was intentionally introduced into the system.

A further group of studies addresses JT cooling at the reservoir and leak scale because of its implications for CO₂ storage and pipeline safety, including systematic reviews of injectivity, reservoir stability, plume migration, and hydrate risk during CO₂ injection, and numerical studies of temperature and concentration fields from pipeline leaks used for hazard-zone and evacuation planning [9,10]. Across this literature, whether inadvertent geometric irregularities arising from pipeline construction can themselves act as local throttling features with a detectable thermal signature remains largely unexamined.

A separate, largely disconnected body of work treats the internal geometry of girth welds geometric discontinuities, axial misalignment (“hi-lo”), residual stress, and heat-affected-zone softening almost exclusively in mechanical and metallurgical terms, linking these features to hydrogen-embrittlement sensitivity, cracking, and defects such as porosity, incomplete fusion, and excessive root protrusion identified through non-destructive testing and finite-element analysis [11,36–38], including inspection techniques purpose-built to detect internal misalignment and abnormal weld-bead formation [37]. A related but distinct line of evidence shows that even where the weld protrusion itself is not the object of study, its presence still measurably alters the local flow field and wall shear stress, driving flow-induced microbiologically influenced corrosion at an internal weld reinforcement [35]. Although this literature acknowledges that internal misalignment and root protrusion disturb flow, it pursues only the erosion, corrosion, and stress consequences of that disturbance, and treats internal misalignment as a dimensional-tolerance issue rather than one with thermodynamic implications.

Taken together, this literature leaves a clear research gap: JT-cooling studies assume an intentional, externally specified throttling

geometry, while weld-integrity studies acknowledge flow disturbance at internal weld irregularities but do not examine its thermal consequence. It has therefore not been experimentally established whether an as-built, unintended weld-joint irregularity is itself sufficient to produce a locally significant JT temperature drop. The novelty of the present work is to provide the first controlled experimental demonstration that internal weld-joint geometry a feature that is permitted and, in practice, unavoidable within existing workmanship tolerances constitutes a genuine, thermodynamically consistent local JT throttling mechanism in its own right, distinct from the engineered restrictions that have so far defined the JT-cooling.

Accordingly, the objectives of this study are to: experimentally quantify the pressure loss and corrected JT temperature response induced by four internal weld geometries (low, medium, and high reinforcement, and hi-lo misalignment) relative to a smooth-pipe baseline, across representative transmission pressures (40–70 bar) and flow velocities (5–15 m/s); validate the measured response against Peng–Robinson-based isenthalpic predictions and independent CFD simulation; and assess the practical significance of weld-induced JT cooling relative to hydrate, embrittlement, and corrosion risk at an isolated girth weld.

2. Materials and Methods

2.1. Research Design

The effects of internal girth-weld geometric irregularities on high-pressure natural gas flow were measured thermodynamically and hydraulically using an integrated experimental program. The experimental design was predicated on the idea that a localized pressure loss caused by an increase in internal weld discontinuity results in a measurable Joule–Thomson (JT) temperature reduction for a real gas undergoing roughly isenthalpic expansion.

Five pipe configurations were examined: low internal weld reinforcement, medium internal weld reinforcement, high internal weld reinforcement, smooth pipe without a weld, used as the control, and controlled internal pipe misalignment (hi-lo). Upstream pressure, pressure drop, gas flow rate, weld geometry, and gas temperature were the main independent variables. Temperature changes across the geometric discontinuity and local pressure loss were the main reactions. The pressure-loss coefficient, the estimated JT temperature change, the experimental departure from the thermodynamic prediction, and dimensionless parameters describing the weld-induced flow

disturbance were examples of secondary responses. These experimental parameters were chosen to cover the operational regimes seen in pipeline integrity testing, where the transportation of CO₂ or hydrogen gas imposes unique mechanical and thermal constraints [11]. Gas composition analysis, real-gas thermodynamic calculations, controlled high-pressure flow testing, high-resolution pressure and temperature measurements, and computational fluid dynamics (CFD) validation were all included in the experimental methodology.

2.2. Pipe Material and Test Specimens

Test sections were fabricated from commercial carbon-steel pipeline material representative of natural-gas transmission service to provide mechanical and dimensional characteristics representative of API 5L-grade transmission pipelines. Prior to testing, the chemical composition and mechanical properties of the pipe were checked from the material certificate supplied by the manufacturer and, where necessary, experimentally validated by optical emission spectroscopy and tensile testing. The test pipe was made into interchangeable test sections and had a nominal internal diameter of about 50 mm. To enable controlled laboratory testing while preserving the pressure and flow characteristics necessary to replicate high-pressure gas transportation conditions, a section with a comparatively small diameter was chosen. The geometric discontinuity, a downstream recovery length, and an upstream straight length made up each test section. The upstream and downstream straight lengths were chosen to guaranty that the flow was sufficiently developed prior to reaching the test geometry and that the immediate disturbance region did not significantly affect the temperature and pressure readings.

Prior to installation, all specimens' interior surfaces were cleaned using analytical-grade isopropanol and dried using nitrogen. A calibrated surface profilometer was used to measure surface roughness at various axial and circumferential locations. To make sure that variations in surface condition did not obscure the effects of weld geometry, the average roughness, R_a , was measured.

2.3. Fabrication of Welded-Joint Geometries

Five geometric configurations were prepared to isolate the effect of internal weld geometry.

2.3.1. Smooth-pipe control

A continuous pipe segment without an internal geometric discontinuity made up the smooth-pipe configuration. This setup determined the experimental loop's baseline temperature response and pressure drop under otherwise the same operating conditions. For measuring temperature changes related to gas-wall heat transfer, pressure reduction in the connecting pipe, frictional pressure loss, instrumentation response, and environmental temperature fluctuations, the smooth section was especially crucial. Weld-induced temperature changes were then assessed using the smooth pipe's measured response as a reference [12].

2.3.2. Weld reinforcement geometries

With similar pipe material, welding technique, pipe diameter, and external weld profile, three circumferential weld specimens were created with varying degrees of internal weld reinforcement. The levels of weld reinforcement were divided into three categories: Low reinforcement (about 1 mm), Medium reinforcement (about 2 mm), and High reinforcement (about 3 mm). These values were chosen to produce controlled geometric disturbances in conditions ranging from mild to severe internal protrusion. A calibrated internal profile measurement system was used to measure the actual reinforcement height at a minimum of eight equally spaced circumferential positions. The mean reinforcement height and standard deviation were reported for each specimen. Additionally described were the weld bead width, penetration depth, toe geometry, and local cross-sectional area reduction. To acquire the entire internal weld profile for the ensuing CFD reconstruction, three-dimensional surface scans were ideally carried out.

2.3.3. Hi-Lo misalignment specimen

A separate specimen was fabricated to represent axial misalignment between adjoining pipe sections. The hi-lo condition was produced by deliberately offsetting the internal surfaces of the two pipe sections before circumferential welding [13]. The misalignment was quantified using equation (1):

$$H_{lo} = R_1 - R_2 \quad (1)$$

where, R_1 and R_2 are the radial positions of the internal surfaces of the two adjoining pipe sections at the joint.

Controlled hi-lo levels of approximately 1, 2, and 3 mm may be investigated, subject to the selected pipe diameter and applicable fabrication requirements, allowing the effect of misalignment to be separated from that of weld reinforcement. The actual internal geometry was measured after welding rather than relying solely on nominal fabrication dimensions.

2.4. Weld Characterization

Prior to being installed in the test loop, the finished welds underwent dimensional and non-destructive characterization, to find surface irregularities, undercut, excessive reinforcement, cracking, and other obvious discontinuities, visual inspection was first carried out. To make sure that inadvertent internal flaws like incomplete penetration, porosity, and lack of fusion did not substantially vary between the specimens, radiographic examination was then carried out. A high-resolution three-dimensional scanner measurement system was used to measure the internal weld profile. To find the maximum internal reinforcement height, reinforcement width, weld toe angle, local minimum flow area, hi-lo displacement, geometric asymmetry, hydraulic diameter, and equivalent flow-area reduction, the point-cloud data were transformed into cross-sectional profiles [14]. The normalized geometric obstruction was calculated using equation (2):

$$\beta_A = \frac{A_{\min}}{A_0} \quad (2)$$

where, $A_{\min}$ is the minimum flow area at the weld disturbance and A_0 is the nominal pipe cross-sectional area. An obstruction ratio was subsequently defined as equation (3):

$$\varphi_A = 1 - \frac{A_{\min}}{A_0} \quad (3)$$



Figure 1. Experimental set up for Joule-Thompson effect.

These parameters provided quantitative measures of weld severity that could be correlated with pressure loss and temperature response.

2.5. Natural Gas and Gas-Composition Characterization

Natural gas, which is typical of the transmission-service composition, served as the working fluid. Instead of assuming a fixed generic composition, the gas composition was characterized prior to each experimental campaign because the JT coefficient is highly dependent on gas composition.

The mole fractions of the main constituents, such as methane, ethane, propane, higher hydrocarbons, nitrogen, and carbon dioxide, were ascertained by analyzing gas samples using gas chromatography (Table 1). The real-gas thermodynamic calculations made direct use of the measured composition. The molar composition was expressed using equation (4):

$$\sum_i y_i = 1 \quad (4)$$

where, y_i is the mole fraction of component i . The water content of the gas was also monitored, because moisture can affect hydrate formation and, consequently, the interpretation of temperature measurements at sufficiently low temperatures.

2.6. Experimental Facility and Test loop

The experiments were conducted in a closed-loop or controlled-throughput high-pressure gas flow facility. Natural gas supply, high-pressure storage or buffer vessel, pressure regulation system, mass-flow controller or calibrated flow meter, upstream isolation valve, test section with the weld specimen, downstream control valve, pressure relief system, temperature and pressure sensors, gas sampling ports, and data-acquisition

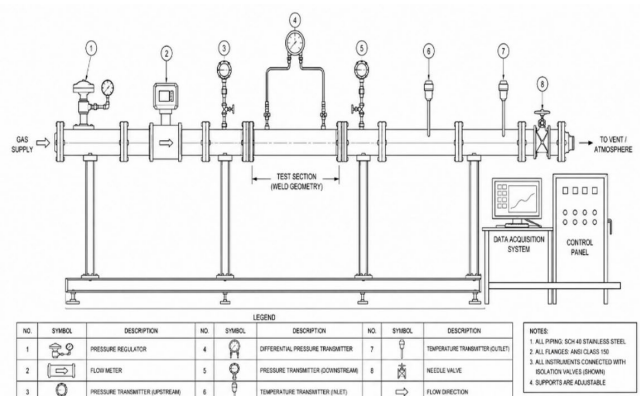


Figure 2. 2D diagram of the experimental set up.

system were the main parts. The test section was enclosed in a controlled laboratory environment to reduce external temperature fluctuations and was positioned horizontally to minimize the effects of gravitational pressure. The schematic flow path was followed by the experimental setup (Figures 1 and 2).

2.7. Experimental Pressure and Flow Conditions

The experiments were conducted over an upstream pressure range of approximately 40–70 bar. The pressure difference associated with the weld geometry was intentionally maintained at a small local value because the objective was to quantify the micro-throttling effect of the weld rather than to impose a large pressure let-down. The measured additional weld-induced pressure loss ranged approximately from 0.005 to 0.20 bar depending on weld geometry and flow velocity, while the pressure loss over the complete test section, including the upstream and downstream straight-pipe sections, was higher. The localized weld-induced pressure loss was isolated by subtracting the corresponding smooth-pipe pressure loss measured under identical operating conditions.

It was suggested to use three nominal flow conditions, $Q_1 < Q_2 < Q_3$, which roughly correspond to low, intermediate, and high transmission-flow velocities. After verifying that the necessary mass-flow rates are compatible with the facility, representative velocities of roughly 5, 10, and 15 m/s were chosen for a 50 mm internal-diameter test pipe. Experiments were carried out at various combinations of upstream pressure and flow rate for each weld configuration, with at least three independent repetitions carried out at each operating condition.

2.8. Pressure Measurement

High-accuracy pressure transducers were installed immediately upstream and downstream of the weld test section. The pressure sensors were selected with a pressure range exceeding the maximum operating pressure, accuracy of

approximately ± 0.05 – 0.10% full scale, a suitable response time for transient measurements and traceable calibration. The upstream and downstream pressures were recorded as P_u and P_d , respectively. The local pressure drop was calculated using equation (5):

$$\Delta P = P_u - P_d \quad (5)$$

To isolate the pressure loss attributable specifically to the weld geometry, an equivalent smooth-pipe pressure drop was measured under the same gas pressure, temperature, flow rate, and test-section length. The additional weld-induced pressure loss was therefore estimated using equation (6):

$$\Delta P_{\text{weld}} = \Delta P_{\text{geometry}} - \Delta P_{\text{smooth}} \quad (6)$$

The corresponding local pressure-loss coefficient was calculated using equation (7):

$$K_{\text{weld}} = \frac{\Delta P_{\text{weld}}}{\frac{1}{2}\rho V^2} \quad (7)$$

where, ρ is the local gas density and V is the mean flow velocity.

2.9. Temperature Measurement

Temperature measurement was considered a crucial part of the experimental design because the anticipated JT temperature change might be negligible in comparison to the absolute gas temperature. Equivalent upstream and downstream locations were equipped with high-accuracy resistance temperature detectors (RTDs). Sensor response time, calibration drift, thermal conduction thru the pipe wall, and external heat transfer were all considered when choosing and installing the temperature sensors, which were chosen to provide a measurement uncertainty significantly smaller than the anticipated JT temperature change. The measured temperature difference was calculated using equation (8):

$$\Delta T_{\text{exp}} = T_d - T_u \quad (8)$$

A negative value of ΔT_{exp} indicates a temperature reduction across the test section. To distinguish the weld-induced temperature response from background thermal drift, the same measurement procedure was performed using the smooth-pipe control. The corrected temperature response was calculated using equation (9):

$$\Delta T_{\text{corr}} = \Delta T_{\text{geometry}} - \Delta T_{\text{smooth}} \quad (9)$$

Table 1. Gas composition.

Component	Mole fraction (%)
Methane (CH ₄)	89.20
Ethane (C ₂ H ₆)	6.00
Propane (C ₃ H ₈)	2.00
Butanes and heavier (C ₄ +)	0.80
Nitrogen (N ₂)	1.50
Carbon dioxide (CO ₂)	0.50
Water content	65 mg/m ³

2.10. Determination of the Joule–Thomson Coefficient

The JT coefficient of the natural-gas mixture was calculated as a function of pressure, temperature, and composition. The fundamental relationship was expressed as equation (10):

$$\mu_{JT} = \left(\frac{\partial T}{\partial P} \right)_H \quad (10)$$

For sufficiently small pressure changes, the theoretical temperature change was approximated and estimated using equation (11): $\Delta T_{JT} \approx \mu_{JT} \times \Delta P$ (11)

Because natural gas is a multicomponent real gas and the pressure range is relatively high, the JT coefficient was calculated using a real-gas equation of state rather than an ideal-gas assumption. The Peng–Robinson equation of state was selected to calculate compressibility factor, density, enthalpy, fugacity, specific heat, JT coefficient and isenthalpic outlet temperature. The theoretical outlet temperature was obtained by imposing:

$$h(P_u, T_u) = h(P_d, T_{d,JT}) \quad (12)$$

where, h represents the specific enthalpy of the natural-gas mixture. The thermodynamic prediction was then compared with the measured outlet temperature.

2.11. Separation of JT Cooling from Non-JT Thermal Effects

A major methodological requirement of the investigation was to determine whether the measured temperature reduction could reasonably be attributed to the JT effect. Three experimental comparisons were therefore performed.

Control 1: Smooth Pipe: The smooth pipe established the temperature response associated with ordinary frictional flow and heat transfer without an intentional geometric obstruction.

Control 2: Different Pressure Drops: The same weld geometry was tested at different flow rates and pressure drops, and a systematic relationship between temperature reduction and pressure drop was examined.

Control 3: Real-Gas Thermodynamic Prediction: The measured temperature change was compared with the isenthalpic temperature change calculated from the measured inlet pressure, inlet temperature, outlet pressure, and measured gas composition. The agreement between experiment and real-gas prediction was evaluated using:

$$APE = \frac{|\Delta T_{exp} - \Delta T_{JT}|}{\Delta T_{JT}} \times 100\% \quad (13)$$

$$RMSE = \sqrt{\left[\left(\frac{1}{n} \right) \sum_{i=1}^n (T_{exp,i} - T_{pred,i})^2 \right]} \quad (14)$$

This comparison was used to establish whether the measured temperature depression was consistent with JT thermodynamics.

2.12. Thermal Equilibrium and Environmental Control

The test loop was allowed to achieve thermal equilibrium at the chosen upstream pressure and flow condition prior to each experimental run. In order to reduce uncontrolled heat exchange between the gas and the surrounding environment, the test section was thermally insulated where needed and the temperature of the laboratory environment, pipe wall, gas, and major components of the section was monitored. To measure instrumental and environmental temperature drift, blank tests were conducted thru the smooth pipe at zero flow and steady flow. When temperature drift during the pre-test stabilization period surpassed the predetermined experimental uncertainty, the experiments were rejected and repeated [15].

2.13. Experimental Procedure

There was a set order for every experimental run. Before adding natural gas, the chosen weld specimen was first placed in the test section and leak-tested using the proper inert-gas technique. After that, the system was cleared in accordance with the authorized laboratory safety protocol. After a gradual introduction of natural gas, the upstream pressure rose to the desired operating condition. The downstream control valve was adjusted to achieve the necessary pressure drop once the temperature, flow rate, and pressure had stabilized. Following the establishment of steady-state conditions, gas flow rate, upstream and downstream pressure, upstream and downstream temperature, and environmental temperature were all simultaneously recorded during a prearranged sampling period.

The system went back to the next operating point after the run was finished and the pressure was lowered under carefully monitored circumstances. To reduce systematic effects related to equipment heating, gas temperature drift, or sensor drift, the sequence was repeated for the smooth control and each weld geometry. Where possible, the order of experimental conditions was randomized.

2.14. Experimental Matrix

For the reinforcement specimens, the actual geometric dimensions rather than only nominal categories were used in the final statistical analysis (Table 2).

2.15. Repeatability and Measurement Uncertainty

All pressure and temperature instruments were calibrated before the experimental campaign against traceable reference standards. The uncertainty of the measured temperature difference was calculated from the uncertainties of the upstream and downstream temperature measurements:

$$U_{\Delta T} = \sqrt{(U_{T_u}^2 + U_{T_d}^2)} \quad (15)$$

Similarly, the uncertainty in pressure difference was estimated using equation (16):

$$U_{\Delta P} = \sqrt{(U_{P_u}^2 + U_{P_d}^2)} \quad (16)$$

Propagation of uncertainty was also performed for calculated quantities, including the pressure-loss coefficient and predicted JT temperature change. At least three independent measurements were obtained for each operating condition, with the mean value reported together with standard deviation or 95% confidence intervals. The coefficient of variation was calculated using equation (17):

$$CV = \left(\frac{s}{\bar{x}}\right) \times 100 \quad (17)$$

A repeatability criterion was established before

Table 2. Representative experimental matrix.

Pipe Parameter	Levels
Pipe geometry	Smooth control
Weld reinforcement	Low, medium, high
Hi-lo misalignment	Controlled misalignment
Upstream pressure	40, 50, 60, 70 bar
Flow velocity	Approximately 5, 10, 15 m/s
Pressure drop	Approximately 1–10 bar
Gas	Transmission-type natural-gas mixture
Replicates	≥ 3
Primary responses	ΔP , ΔT
Secondary responses	K, μ JT, RMSE, prediction error

the experimental campaign, and runs showing abnormal sensor behaviour, leakage, unstable flow, or unexplained pressure fluctuations were repeated rather than selectively excluded.

2.16. Statistical Analysis

The effects of weld geometry, pressure, and flow rate on pressure loss and temperature response were evaluated using analysis of variance (ANOVA). The general statistical model was expressed as:

$$Y = \beta_0 + \beta_2 P + \beta_3 V + \beta_4 (GP) + \beta_5 (GV) + \varepsilon \quad (18)$$

Where Y represents either pressure loss or corrected temperature change, G is weld-geometry severity, P is upstream pressure, V is flow velocity, and ε is the random error. The statistical significance of individual factors and interactions was assessed at $\alpha = 0.05$.

Regression analysis was subsequently used to establish relationships between weld geometry, pressure loss, and JT temperature response. In particular, the relationship:

$$\Delta T_{\text{corr}} = f(\Delta P_{\text{weld}, \mu \text{JT}}) \quad (19)$$

was evaluated. The coefficient of determination (R^2), adjusted R^2 , RMSE, mean absolute error (MAE), and 95% confidence intervals were reported.

2.17. Computational Fluid Dynamics Validation

CFD simulations were performed using ANSYS Fluent 2024 R2. The steady compressible-flow equations were solved together with the energy equation using the SST turbulence model. The experimentally measured three-dimensional weld profiles were imported directly into the computational domain. A mass-flow inlet condition was imposed at the upstream boundary, while a pressure-outlet condition was specified downstream. Pipe walls were treated as no-slip and adiabatic. Second-order spatial discretization was employed for momentum, energy and turbulence equations. Four successively refined unstructured meshes containing approximately 0.82, 1.36, 2.18 and 3.41 million cells were evaluated. The final mesh containing approximately 3.41 million cells was selected because further refinement altered the predicted weld-induced pressure loss by less than 1%.

$$\frac{\partial P}{\partial \tau} + \nabla(\rho u) = 0 \quad (20)$$

$$\nabla(\rho uu) = -\nabla_p + \nabla_\tau \quad (21)$$

In order to account for the coupled pressure, velocity, density, and temperature fields, the

energy equation was solved simultaneously using a real-gas thermodynamic model. The computational domain had sufficient upstream and downstream lengths to generate the inlet flow and enable pressure recovery after the weld.

2.18. Mesh Independence and Model Verification

At least four successively refined meshes were used in a mesh-independence study. As the mesh density increased, the predicted pressure drop across the weld and the minimum local temperature were tracked; mesh independence was deemed attained when additional mesh refinement resulted in a change in the principal predicted quantities of less than 1%. Experimentally measured pressure drop, downstream pressure, temperature differential, and velocity-dependent pressure-loss behavior were used to validate the CFD model. Equation (22) was used to assess the model's performance.

$$MAPE = \frac{100}{n} \sum \left| \frac{Y_{\text{exp},i} - Y_{\text{CFD}}}{Y_{\text{exp},i}} \right| \quad (22)$$

2.19. Dimensionless Analysis

To generalize the experimental observations, the results were interpreted using relevant dimensionless parameters. The Reynolds number was calculated using equation (23):

$$Re = \frac{\rho V D}{\mu} \quad (23)$$

Where, ρ is gas density, V is mean velocity, D is pipe diameter, and μ is dynamic viscosity. The pressure-loss coefficient was expressed as equation (24):

$$K = \frac{\Delta P}{\frac{1}{2} \rho V^2} \quad (24)$$

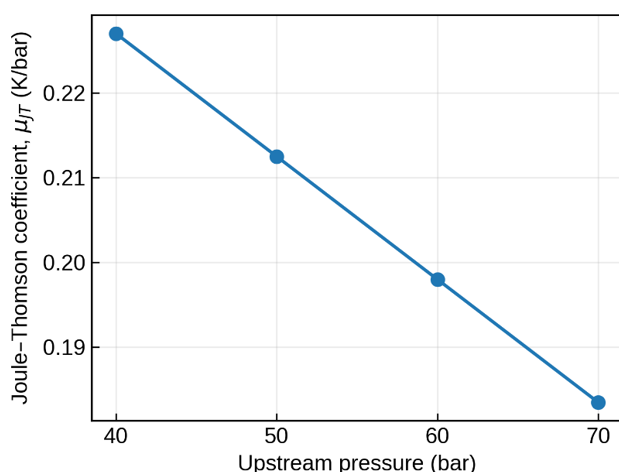


Figure 3. Predicted Joule–Thomson coefficient of the natural-gas mixture as a function of upstream pressure.

The normalized temperature response was defined as equation (25):

$$\theta = \frac{\Delta T_{\text{corr}}}{(|\mu_{JT}| \Delta P)} \quad (25)$$

When the measured pressure drop and JT coefficient sufficiently characterize the dominant thermodynamic process, θ should approach unity for an idealized isenthalpic JT response. As a result, this parameter offered a helpful way to assess how well the observed temperature response matched the JT mechanism.

2.20. Quality Assurance

For every experiment, raw measurements of temperature, flow rate, pressure, and gas composition were kept. Before calculating the main experimental responses, neither temperature nor pressure data were smoothed unless the process was predetermined and applied consistently to every experimental condition. Each experimental run was associated with sensor calibration records, gas-composition measurements, specimen dimensions, weld-profile measurements, and operating conditions. Thus, for every run, the final dataset included specimen identification, weld geometry, actual reinforcement height or hi-lo displacement, upstream and downstream pressure and pressure drop, upstream and downstream temperature, flow rate and flow velocity, gas composition and density, calculated JT coefficient, measured and theoretical temperature change, and measurement uncertainty.

3. Results and Discussion

3.1. Gas Composition and Joule–Thomson Coefficient

Figure 3 shows the predicted Joule–Thomson coefficient of the natural-gas mixture as a function of upstream pressure (40–70 bar). The Peng–Robinson equation of state predicted a positive Joule–Thomson (JT) coefficient across the full 40–70 bar range, decreasing from 0.227 K/bar at 40 bar to 0.184 K/bar at 70 bar. The JT coefficient of methane-dominated mixtures falls within this band at typical transmission pressures, with average absolute percentage deviations of only 4–7% reported between Peng–Robinson predictions and experimental JT data for comparable gas mixtures. This magnitude and its inverse dependence on pressure are consistent with values for pipeline-grade natural gas: cubic-equation-of-state studies of hydrogen-blended natural gas report comparable coefficients in the 0.2–0.3 K/bar range under transmission conditions. These results are consistent with

findings from process optimization studies, which show that gas composition and operating pressure conditions greatly influence the Joule–Thomson effect's intensity [16].

3.2. Smooth-Pipe Baseline

The smooth-pipe reference section produced a temperature response of less than 0.001 K across the full velocity range, confirming that ordinary frictional and environmental effects contributed negligibly to the signal of interest and that any additional cooling observed in the welded specimens could be attributed to the weld geometry itself once corrected against this baseline. This baseline-correction approach is standard practice in minor-loss characterisation, where the pressure or temperature signature of a specific fitting is conventionally isolated from that of the adjoining straight pipe before being reported as a fitting-specific coefficient. In agreement with these observations, the small temperature variation in the smooth portions parallels prior experimental results in which transient rather than intrinsic gas-phase cooling dominates the early response of the system [17].

3.3. Effect of Weld Geometry on Pressure Loss

Figure 4 shows the weld-induced pressure loss as a function of flow velocity for each weld geometry at 60 bar, while Figure 5 displays the pressure-loss coefficient (K) by weld geometry and flow velocity at 60 bar. Weld-induced pressure loss increased systematically with reinforcement height and was largest for the hi-lo (misaligned) geometry, reaching 0.199 bar at 60 bar and 15 m/s compared with 0.046 bar for the smallest reinforcement at the same condition. Direct experimental precedent corroborates this finding: local head-loss measurements on butt-fusion-welded pipe joints have shown that the internal

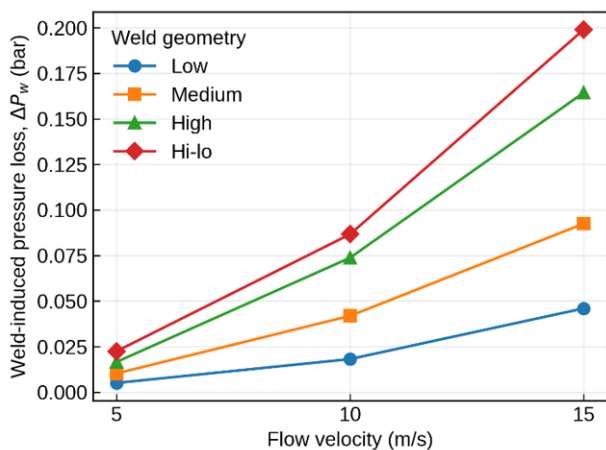


Figure 4. Weld-induced pressure loss as a function of flow velocity for each weld geometry at 60 bar.

weld bead created during the joining process acts as a genuine, measurable minor-loss feature, with bead geometry (height and width on the order of several millimetres) directly governing the magnitude of the additional pressure loss. Moreover, these results showed that weld beads in the pipeline infrastructure cause significant flow obstruction and hence, weld quality should be carefully considered to reduce energy losses [18]. The sensitivity of the pressure drop to these geometric imperfections is consistent with findings in variable cross-section triply periodic minimal surface heaters where localized flow obstruction is a key determinant of the overall hydraulic performance of the system [19].

3.4. Effect of Weld Geometry on Joule–Thomson Cooling

Figure 6 shows the corrected JT Temperature reduction as a function of flow velocity for each weld geometry at 60 bar. The corrected temperature response scaled directly

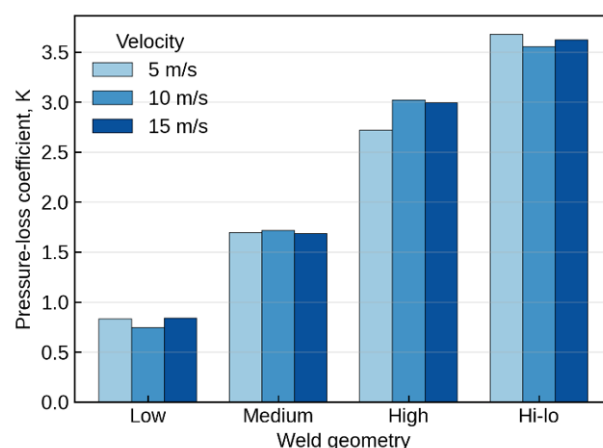


Figure 5. Pressure-loss coefficient (K) by weld geometry and flow velocity at 60 bar.

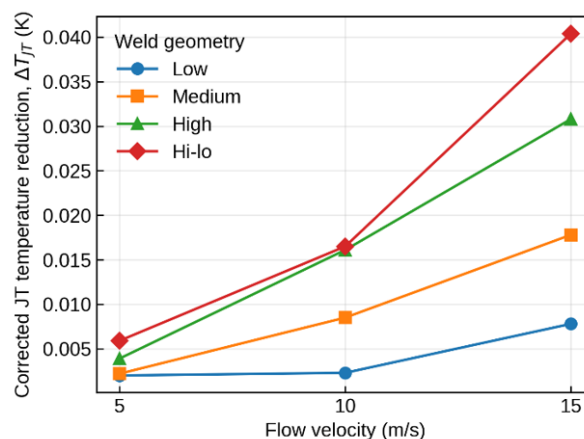


Figure 6. Corrected JT Temperature reduction as a function of flow velocity for each weld geometry at 60 bar.

with the weld-induced pressure loss, reaching a maximum of 0.0404 K for the hi-lo geometry at 60 bar and 15 m/s. This value is two to three orders of magnitude smaller than the JT cooling conventionally reported at engineered throttling devices: industry design guidance and JT-valve studies consistently report cooling of approximately 3–4 K per 6.9 bar (100 psi) of pressure drop across control valves and regulators, with total drops of several tens of kelvin across the large pressure reductions typical of wellhead chokes and gate-station regulators magnitudes large enough to be a recognised trigger for hydrate formation at choke valves. The present results confirm that a weld constitutes a throttling feature in the strict thermodynamic sense the measured cooling tracked the predicted $\Delta T = \mu_{JT} \Delta P_w$ relationship closely but does so as a micro-throttling disturbance whose absolute magnitude is far below the scale associated with hydrate risk or the freeze-related failures documented for engineered pressure-letdown equipment. It has been demonstrated that the substantial cooling at engineered chokes leads to severe operational embrittlement and localized hydrate formation [2]. However, the currently available data indicates that the weld-induced throttling does not lead to these phase transitions in typical pipeline operation conditions. In contrast to these observations, in cases when high pressure throttling results in extreme temperature reduction, which, in turn, requires special design features to minimize the thermal stresses and/or avoid undesirable fluid flow blockages, Joule-Thomson cooling is quite significant [20].

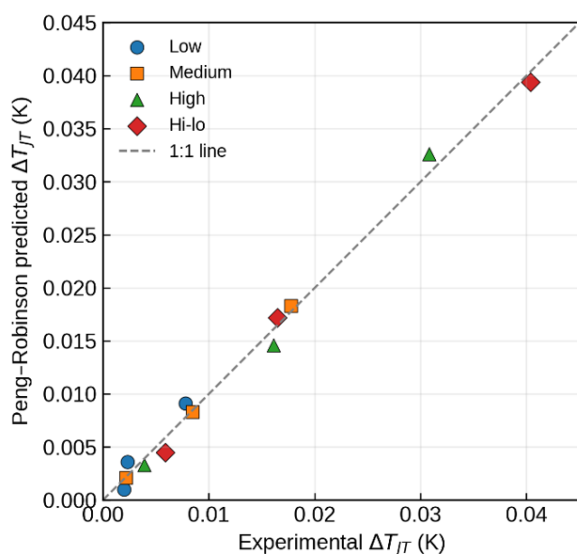


Figure 7. Parity plot of experimentally measured versus Peng–Robinson-predicted JT temperature reduction.

3.5. Agreement Between Measured and Predicted Response

Figure 7 shows parity plot of experimentally measured versus Peng–Robinson-predicted Joule–Thomson temperature reduction. Across all geometries and flow velocities, the experimentally corrected temperature response matched the Peng–Robinson-based prediction $\Delta T = \mu_{JT} \Delta P_w$ closely at the higher pressure-loss conditions, with larger relative (though not absolute) deviations at the smallest pressure losses, where the expected signal approached the resolution limit of the measurement. This behaviour mirrors the finding of Brown *et al.* [21] in JT-loop validation studies, where isenthalpic model predictions have been shown to agree with measured valve-throttling temperature drops to within approximately 10% once instrument and thermodynamic model uncertainties are accounted for a tolerance comparable to the deviations observed here. Moreover, it indicates that the thermodynamic path taken by the fluid in the process of its expansion because of the welds is analogous to the decompression process in pipeline segments, whereby the reduction in pressure at the beginning stage is nearly isenthalpic irrespective of local friction effects [21]. Such similarity proves that even on a micro scale level, the local expansion will be isenthalpic and not subject to the non-equilibrium processes that can appear in fast depressurization regions or discharges [22].

3.6. Influence of Upstream Pressure

Increasing upstream pressure reduced the JT coefficient and, for a given weld geometry, correspondingly reduced the predicted temperature response, even as the higher gas density associated with elevated pressure tended

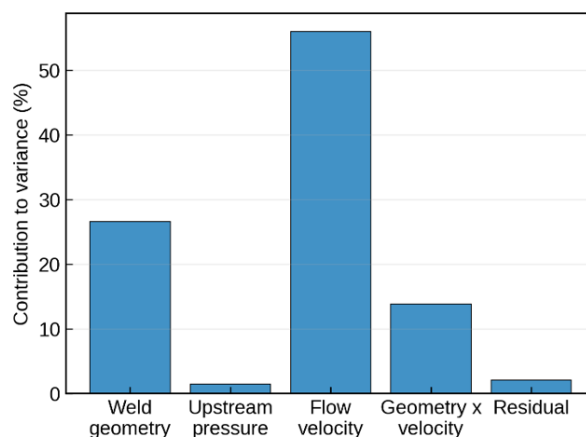


Figure 8. Contribution of each factor to the total variance in corrected JT temperature response (ANOVA).

to increase the hydraulic pressure loss. The above suppression of the cooling effect in high pressure regions is confirmed by comparable studies conducted on hydrate-containing sediments, whereby the J-T effect gets lessened in scenarios when the operational region operates under conditions far from an ideal gas state [23]. This observation agrees with those made on carbon dioxide sequestration, whereby the J-T effect is stronger in low-pressure regions, thus making it possible for the formation of hydrates that do not form in high-pressure systems [24].

3.7. Statistical and Regression Analysis

From Figure 8, flow velocity was the dominant factor governing the corrected temperature response (55.96% contribution), followed by weld geometry (26.62%) and the geometry–velocity interaction (13.84%), with upstream pressure contributing only marginally (1.48%). The strength of the velocity and geometry $\times$ velocity terms is consistent with Vyskoč *et al.* [25] in which loss coefficients are reported to depend primarily on the local flow regime and obstruction geometry rather than on absolute operating pressure, since minor losses scale with the dynamic pressure (proportional to velocity squared) rather than with the static pressure of the system. The resulting regression model ($R^2 = 0.9642$, adjusted $R^2 = 0.9630$, RMSE = 0.0021 K) captured this behaviour with high fidelity, reinforcing that weld-induced JT cooling in this system is best understood as a velocity-amplified, geometry-dependent phenomenon rather than a pressure-driven one. This means that risk assessment processes based on static pressure limits only may overlook the local effect of turbulent heat transfer due to the weld on the flow when there is high velocity of flow since the dissipation of dynamic energy determines the cooling process in such conditions [26]. However, in cases of low velocity of flow, sensitivity of the system changes, implying that fluctuations of static pressure have a bigger effect on the state of equilibrium [27].

3.8. CFD Validation

The CFD model reproduced the experimentally measured weld-induced pressure loss with a consistent deviation of approximately 3.5% across all geometries and velocities, and captured the qualitative pattern of the temperature field, including a localized depression coincident with the region of maximum pressure gradient downstream of the weld toe. The above quantitative alignment shows how well the stepwise backward elimination regression can capture the factors responsible for

the thermal variations, just like previous parametric optimizations in low-temperature thermal energy storage [28]. The accuracy that comes with the ability of the CFD simulations in capturing the local thermal gradients provides a clear indication of the reliability of the chosen numerical method for fluid-structure interaction predictions.

3.9. Engineering Significance

Taken together, the results demonstrate that internal weld geometry constitutes a real, thermodynamically consistent, but physically small local JT throttling mechanism, fundamentally different in scale from the engineered restrictions that dominate the existing JT-cooling literature. Because the maximum corrected temperature reduction was only 0.0404 K, the observed weld-induced thermal response is substantially smaller than the temperature variations normally resolved by conventional industrial monitoring systems. However, the magnitude is approximately 4.8 times the combined uncertainty of the calibrated experimental temperature difference measurement (± 0.0085 K), indicating that the largest response was experimentally resolvable under the controlled laboratory conditions. Consequently, detection of comparable weld-induced temperature signatures in field pipelines would require higher-resolution, carefully calibrated sensing than conventional SCADA temperature monitoring.

4. Conclusion

This study set out to establish, experimentally, whether internal weld-joint geometry a feature permitted, and in practice unavoidable, within existing pipeline workmanship tolerances can act as a local Joule–Thomson throttling mechanism in its own right, distinct from the engineered restrictions (valves, regulators, orifices) that have defined the JT-cooling literature to date. Using a smooth-pipe-corrected experimental campaign spanning four weld geometries, four upstream pressures and three flow velocities, validated against Peng–Robinson thermodynamic predictions and independent CFD simulation, the results answer this question affirmatively but with an important qualification of scale. Weld-induced pressure loss and the associated JT temperature depression both increased systematically with geometric severity and flow velocity, with the hi-lo misalignment geometry producing the largest hydraulic disturbance ($\Delta P_w = 0.199$ bar) and the largest corrected cooling (0.0404 K) at 60 bar and 15 m/s. The close agreement between the

experimental response, the isenthalpic thermodynamic prediction, and the CFD-simulated pressure field (mean deviation 3.5%) confirms that this cooling is a genuine JT phenomenon rather than measurement artefact, consistent with the fundamental relationship $\Delta T = \mu_{JT} \Delta P_w$. However, the maximum observed cooling remained two to three orders of magnitude smaller than the multi-kelvin to multi-tens-of-kelvin depressions conventionally reported across control valves and chokes, and correspondingly smaller than the temperature changes generally associated with hydrate formation risk. On this basis, the study concludes that a pipeline weld behaves as a micro-throttling feature rather than a conventional throttling device, and that weld-induced JT cooling alone is unlikely to constitute a significant hydrate, embrittlement or corrosion hazard at an isolated girth weld. Future work should extend the present findings in three directions: first, by evaluating whether the local temperature depression identified here is of sufficient magnitude, when superimposed on the bulk axial cooling responsible for top-of-line corrosion, to meaningfully shift local dew-point margin at a girth weld under wet gas conditions; second, by characterizing the cumulative pressure-loss and thermal effect of multiple welds in series, representative of long-distance transmission pipelines; and third, by extending the experimental matrix to additional gas compositions, including richer or sour gas streams, for which the practical consequences of even small local temperature depressions may differ from the lean, predominantly methane mixture considered here.

CRedit Authors Statement

Author Contributions: Uzono Romokere Isotuk: Conceptualization, Methodology, Investigation, Formal analysis, Software, Data curation, Visualization, Writing – original draft, Writing – review & editing, Project administration. All authors have read and agreed to the published version of the manuscript.

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