Design and Validation of a Kiel-Wall-Static Baseline for Mill Primary-Air Differential Pressure Verification

Author: Brandon Martin
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Abstract

Primary-air (PA) venturi differential pressure (Δp) is central to coal mill control. In the Huntly Rankine installation, the in-situ piccolo array resides in the venturi throat, whereas the manual verification porting is approximately one metre downstream near the under-bowl entrance. Legacy manual checks used a plain pitot with a "local" static on the probe body; those data are now suspected to be partially artefactual. This paper develops a physically correct, traceable alternative: a shrouded total-pressure (Kiel) head combined with a co-planar wall static at the measurement plane. We derive the yaw error for plain pitots, quantify axial-plane mismatch, show how to map downstream measurements back to the throat using geometry alone, and give a regression framework that preserves continuity with historical datasets while removing bias. The approach is anchored in ISO 5167 venturi principles and standard pressure-measurement practice [1–3], and it replaces orientation-dependent readings with an orientation-agnostic baseline whose combined uncertainty is typically in the 3–5 % band when implemented as described.

Nomenclature

A_t, A_s, throat and downstream cross-sectional areas, respectively
$\beta = d_t/D_1$, venturi diameter ratio (throat to upstream) [1]
$r = A_s/A_t$, downstream-to-throat area ratio
p_t, p_s, total and static pressure (local)
$q = \frac{1}{2} \rho V^2$, dynamic pressure
ρ, T, density and absolute temperature
Δp_{vent}, upstream–throat venturi differential pressure [1,2]

1. Background and problem framing

The mill's DCS Δp originates from piccolo tubes mounted in the venturi throat of the primary-air line. Manual verification cannot be made in that plane; the access sockets are roughly a metre downstream where the duct area is larger and the flow is recovering through a diffuser. Historically, a plain pitot plus a "local" probe static was inserted at these downstream sockets and its indicated dynamic pressure compared directly to the DCS throat Δp. Two issues are intrinsic to that practice. First, a plain pitot under-reads with yaw according to $\cos^2(\theta)$ [2,8]; residual swirl or minor misalignment in the throat or diffuser can be on the order of ±10–20°, which is already a several-percent effect. Second, even when total and static are co-planar downstream, comparing that downstream dynamic to a throat-referenced signal without geometric mapping introduces a deterministic bias that depends on the area ratio $r=A_s/A_t$ and, weakly, on density ratio; this follows from continuity and Bernoulli [1,2]. ISO 5167 requires co-planar sensing for differential devices and, when different planes are compared, a geometry-consistent transformation[1,2]. Neither effect is consistent with ISO 5167's co-planar total/static ideals for differential devices [1].

A physically correct manual baseline should (i) be insensitive to yaw so that indexing is unnecessary, (ii) use a true static taken in the same axial plane as the total, and (iii) if measured away from the throat, be mapped back to the throat using geometry, not ad hoc factors. Kiel heads meet criterion (i) by design [4–6], and wall statics meet criterion (ii) when installed flush at the target plane and away from large disturbances [3,7]. Criterion (iii) is satisfied by continuity alone [1,2].

2. Governing assumptions

Flow is single-phase air (pre-coal) with Mach number $M \ll 0.3$, so compressibility corrections are small and the gas expansion factor $Y \approx 1$ for Δp–flow relationships in ISO 5167 venturi meters [1]. The Reynolds number at operating conditions is large enough that wall static readings at a throat plane are circumferentially uniform to within a few pascals for healthy geometry [1,3,7]. Temperature and pressure differences between the downstream measurement plane and the throat are modest, so ρ_t/ρ_s can be taken as ≈1 to first order and bounded from thermocouple measurements if needed [3].

3. Theory

3.1 Yaw error of a plain pitot

Let the true local speed be V in direction ê, density ρ, and the pitot axis be yawed by angle θ. Resolving the velocity component along the pitot axis gives

$Vaxis = V \cos\theta.$

With a correct static, the indicated dynamic pressure is

$qpitot = ½\, \rho\, Vaxis^2 = ½\, \rho\, V^2 \cos^2\theta = qt \cos^2\theta.$

Hence the fractional error is

$\varepsilon(\theta) = (qpitot - qt)/qt = -\sin^2\theta$ [2,8].

For θ = 10°, 15°, 20° the under-reads are approximately 3.02 %, 6.70 %, and 11.70 % respectively (exact trigonometric values). The small-angle rule $\varepsilon \approx -\theta^2$ (θ in radians) is a useful heuristic [2].

3.2 Kiel total pressure and orientation immunity

A Kiel head surrounds the total port with a short shroud that conditions local flow and makes the sensed stagnation pressure nearly independent of yaw and pitch over wide angular ranges. Properly proportioned heads exhibit accuracy within a few percent even to ±20° or more in subsonic regimes, as reported by vendors and laboratory characterisations [4–6]. This property allows a single probe to be traversed without re-indexing at each point, removing operator-dependent yaw error.

Figure 1 Kiel Probe

3.3 Static pressure measurement at a plane

Static pressure is the isotropic thermodynamic pressure field; the correct way to sense it in an internal flow is via a flush wall tap or a dedicated static tube whose lip does not admit kinetic head [3,7]. A properly deburred, flush wall tap at a chosen axial cross-section reads the plane's static and is agnostic to instrument yaw. In an axisymmetric venturi throat (or a well-defined diffuser plane), circumferential variation of static is typically very small compared with dynamic pressure at operating Reynolds numbers [1,3,7].

3.4 Mapping a downstream measurement back to the throat

Suppose the manual probe operates at a downstream cross-section of area A_s while the in-situ piccolo array is at the throat of area A_t. Define

$r = As/At > 1.$

For steady, single-phase flow the mean axial velocities satisfy continuity:

$Vt = r\,Vs.$

If the downstream plane uses a Kiel total and co-planar static, its dynamic is

$qs = ½\,\rho s\,Vs^2.$

The throat dynamic is then

$qt = ½\,\rho t\,Vt^2 = r^2\,(\rho t/\rho s)\,qs.$

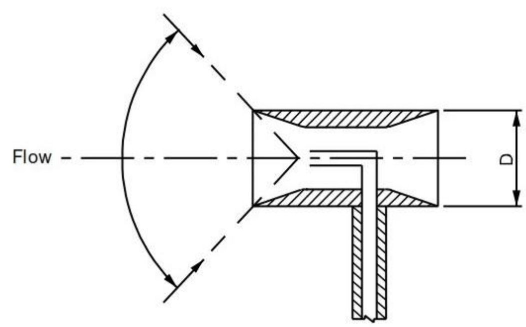

Figure 2 Kiel Cross Section

Primary-air temperature and pressure usually change only weakly between these planes; ρ_t/ρ_s is therefore close to unity, and the geometry term dominates [1–3]. This kinematic mapping does not depend on diffuser losses or discharge coefficients; those affect the Δp-flow conversion, not the algebraic relation between plane-wise dynamic pressures [1,2].

3.5 Axial mismatch error (downstream static with throat total)

If total and static are taken from different axial planes, e.g., throat total and downstream static; the indicated "dynamic" is biased by the plane-to-plane static change. Bernoulli gives

$ps, 2 - ps, t \approx ½ \rho (V\_t^2 - V\_2^2) = q\_t (1 - 1/r^2)$,

so the bias is

$q * - qt \approx - qt (1 - 1/r^2)$

i.e., an under-read by a fraction

$(1 - 1/r^2)$ [1,2].

For r = 1.15 this is ≈24.4 %; for r = 1.05 it is ≈9.3 %; far larger than circumferential tap-to-tap differences at a single plane [1,3].

3.6 Venturi throat equivalence for DCS comparison

For an ISO 5167 venturi operating at low Mach number, the ideal relation is

$\Delta pvent \approx (1 - \beta^4)$ q_t

with

$\beta = dt/D1$ [1,2].

Combining with the downstream mapping yields

$\Delta pvent \approx (1 - \beta^4) r^2 (\rho t/\rho s) qs$,

which is the correct transformation to compare a downstream measurement to a throat-based DCS Δp [1,2].

4. Measurement design

The baseline consists of a single insertion stem carrying a Kiel total port whose sensing plane is aligned with the chosen cross-section, combined with a fixed, flush wall static drilled at the same axial station. The wall static is placed circumferentially away from large disturbances; typically 90-180° from the 2-inch access; with the internal lip flush-ground and carefully deburred [3,7]. A 3-valve HI/LO/equalize manifold allows in-situ zeroing and protects the differential transducer from transients. The thermodynamic state is captured by a grounded-junction thermocouple at the sensing plane; using p_s from the wall tap and T from the thermocouple, density is computed as

$\rho = ps/(R T)$

for low-Mach conditions [3]. This geometry achieves three things simultaneously: the Kiel head removes the $\cos^2(\theta)$ yaw penalty of a plain pitot and therefore eliminates indexing [4–6]; the static is a true plane-wise quantity independent of probe orientation or proximity [3,7]; and when the verification plane is not the throat, the mapping to the throat dynamic involves only the measured q_s, the known area ratio r, and a small density-ratio correction bounded by temperature [1–3].

5. Rigorous critique of the legacy method

The legacy arrangement combined a yaw-sensitive total with a "local" static on the same stem. Two independent mechanisms explain reported "local static fluctuations." First, yaw sensitivity: with a modest misalignment of 10°, the indicated dynamic falls by ≈3 %, and at 20° by ≈12 %, as given by $\varepsilon = - \sin^2 \theta$ [2,8]. Second, static contamination and interference: a static hole on the stem near the stagnation port is exposed to acceleration, wake, and crossflow; true static must be sensed via a flush wall tap or dedicated static tube [3,7]. A third mechanism is axial-plane mismatch: using a downstream static with a throat-like total introduces a bias of magnitude $qt\ (1 - 1/r^2)$ that can reach 10–30 % for common geometry, which is an order of magnitude larger than circumferential variation at a plane [1,2].

6. Uncertainty and traceability

Let
$urel \approx \sqrt{(uyaw^2 + ustatic^2 + utrans^2 + u\rho^2)}$
denote the combined relative standard uncertainty. For the legacy method, u_yaw is set by $|\cos^2 \theta - 1|$; with θ within ±10-20° this term alone is 3-12 % [2,8]. The static contamination term u_{static} is installation-specific but typically several percent when the static is on the stem [3,7]. The transducer contribution u_{trans} for a ±500 Pa differential at 0.25 % FS is ±1.25 Pa, which is ~0.4-0.8 % when q is 150-300 Pa; the density term from temperature is ~0.3 % per kelvin at ~390 K [3]. For the proposed Kiel-wall-static arrangement, u_{yaw} collapses to a few percent or less across ±20° in subsonic ducts [4–6], and u_{static} collapses to the plane's circumferential variation, typically a few pascals for healthy throats [1,3,7]. Consequently, the combined uncertainty moves from double-digit percent to low single-digit percent without exotic hardware.

7.1. Contextualising the S-Type Pitot in Primary-Air Verification

The S-type pitot tube, consisting of two opposing impact ports oriented 180 degrees apart, has a long history of use in emissions monitoring. Standards such as EPA Method 2 in the United States and ISO 10780 internationally explicitly recognise the instrument as an accepted means of measuring velocity in large combustion stacks. Its appeal lies in mechanical simplicity, robustness in particulate-laden or high-temperature gases, and reduced yaw sensitivity compared with a plain pitot tube. A calibration coefficient of approximately 0.84 is conventionally applied, and within those bounds the device provides repeatable results that have been deemed sufficient for regulatory purposes.

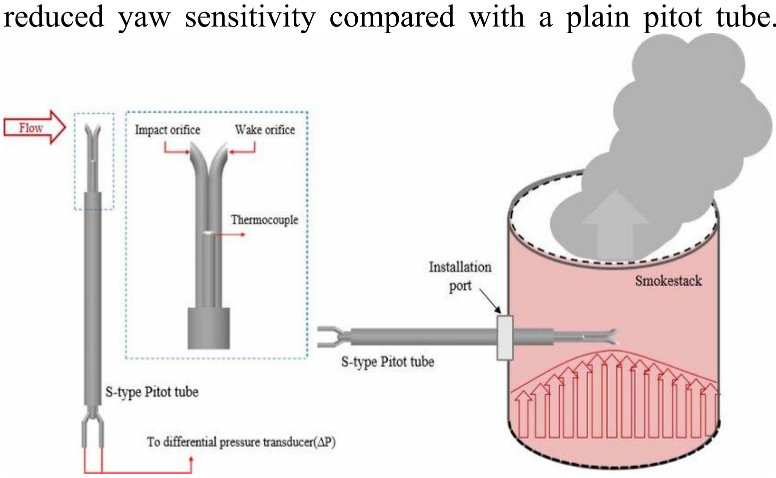

Figure 3 S Type Pitot Tube

In stack environments the priorities differ from those in process control ducts. Gas flows in stacks are highly non-uniform, often with swirl and particulate entrainment, and measurement is mandated for compliance rather than for precision process verification.

Under those circumstances, an empirically corrected velocity reading, even with a larger uncertainty band, is considered acceptable.

7.2. Applicability to Primary-Air Ducts

The primary-air venturi environment presents a different measurement challenge. The piccolo tube array in the throat is intended as a metering device within a controlled geometry, where the goal is to derive a reliable differential pressure–flow relationship for mill operation. Unlike stack gas, the medium is hot, clean air before coal injection, so fouling and soot loading are minimal. This reduces the value of the ruggedness that motivated widespread S-type adoption. While the S-type can certainly produce repeatable measurements, its reliance on an empirical calibration constant and its residual yaw dependence mean it may not provide the same level of metrological rigour as a Kiel head combined with a flush wall static.

7.3. Comparative View

S-Type Pitot

- Strengths: Recognised in international stack standards, relatively tolerant to yaw, robust in dirty flow, no wall tap required.
- Limitations: Requires application of an empirical constant, retains residual yaw error, uncertainty typically in the 5 to 10 percent range under duct conditions.

Kiel-Wall Static Arrangement

- Strengths: Near yaw-independence by design, true static measurement at the same axial plane, directly compatible with ISO 5167 venturi formulations, uncertainties typically within 2 to 5 percent.
- Limitations: Slightly more demanding in installation, requiring a wall static tap and careful alignment of the sensing plane.
- Easily reproducable

7.4. Summary Position

Both instruments have legitimate roles. The S-type pitot is a pragmatic tool where robustness and regulatory precedent are paramount. The Kiel-wall-static arrangement is more appropriate where the need is for a rigorous, first-principles baseline against which process metering devices can be evaluated. In the specific case of primary-air venturi verification, the Kiel-wall-static system provides a stronger standards basis, reduced uncertainty, and a direct linkage to the governing flow equations that underpin the DCS piccolo system.

8. Preserving historical continuity

To maintain comparability with archived datasets while correcting the physics, record in parallel the corrected dynamic

$\Delta p_{correct} = p_{t,Kiel} - p_{s,wall}$

at the verification plane (mapped to throat as needed) and the legacy dynamic

$\Delta p_{legacy} = p_{t,legacy} - p_{s,legacy}$.

Fit

$\Delta p_{correct} = \alpha\, \Delta p_{legacy} + \beta$

across several steady primary-air setpoints to obtain a translation that preserves trends while removing bias [2,3]. Because both channels are simultaneously exposed to the same process variability, the regression parameterises the legacy bias without losing operational information.

9. Implementation and verification

Install one flush wall static at the measurement plane, ideally 180° around from the 2-inch access (or 90° if 180° is not feasible), and align the Kiel sensing plane with that axial station [3,7]. Equalise HI and LO on the wall static to zero the differential, then acquire short time-averages at each vertical position and at several primary-air setpoints. At a mid-height point perform a yaw sweep; the legacy plain pitot will follow $\cos^2 \theta$ while the Kiel head remains essentially flat within a few percent over ±20° [4–6,8]. If the verification plane is not the throat, transform q_s to q_t using $r^2(\rho_t/\rho_s)$ from geometry and temperature, then compare to the DCS Δp via $\Delta p_{vent} \approx (1 - \beta^4)\, q_t$ [1,2]. Apply a modest first-order lag to the computed baseline to match transmitter/impulse-line dynamics before time-aligned comparison.

10. Discussion

Separating the roles of total and static into a yaw-immune total (Kiel) and a co-planar wall static restores the physical meaning of dynamic pressure at a plane. The mathematics is minimal; continuity for mapping between planes and ISO 5167 relations for venturi Δp, and the standards basis is mainstream [1–3]. Historical curves are retained by a single regression mapping from the legacy construct to the corrected construct, avoiding the institutional cost of discarding archives while ceasing to preserve their biases.

11. Conclusion

A manual baseline that uses a Kiel total and a co-planar wall static at the measurement plane, with geometric mapping to the venturi throat when required, replaces orientation-dependent, interference-prone readings with a traceable measure of dynamic pressure. Uncertainty is dominated by instrument resolution and small circumferential variation rather than by yaw and axial mismatch. The approach aligns with ISO 5167 principles, inherits the well-documented yaw immunity of Kiel heads, and offers a regression pathway to preserve legacy datasets without perpetuating their biases [1–6].

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