DESIGN AND ANALYSIS OF CIRCULAR WELD NECK FORGED FLANGE AND BOLTS USED IN GAS PIPELINES USING APPENDIX 2 ASME PRESSURE VESSEL CODE

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ABSTRACT—The design and analysis of a circular weld neck forged flange with its bolted joint are performed to ensure structural integrity and leak-proof operation in gas pipeline systems. This study follows the ASME Boiler and Pressure Vessel Code (BPVC), Section VIII, Division 1, with primary emphasis on Appendix 2, which governs flange design through gasket-seating requirements, bolt load calculations, and flange stress evaluation. Material selection and allowable stresses are based on ASME BPVC Section II, Part D, while dimensional and pressure-temperature ratings are aligned with ASME B16.5. Bolt loads are evaluated for both operating and gasket seating conditions, ensuring adequate sealing performance. Stress verification is carried out to maintain safety against yielding, leakage, and excessive flange rotation. Analysis using PVElite 2008 confirms all stresses within allowable limits for SA-516 Grade 60 (flange) and SA-193 Grade B7 (bolts). The flange rigidity index $J = 0.681 \leq 1.0$, and MAWP of 7.3 bar exceeds the 6.0 bar design pressure by 21.7%. All ASME code checks pass.

I. INTRODUCTION

Flanged joints are among the most critical sealing elements in pressure vessels and gas pipeline systems. Their reliable performance is essential to prevent leakage, structural failure, and process disruption. Weld neck flanges, in particular, are the preferred choice for high-pressure and high-temperature applications due to their integral hub geometry, which distributes bending stress gradually from the connecting pipe into the flange ring, minimising stress concentration.

This paper presents the complete design and structural analysis of the Channel Flange of the AEM Heat Exchanger (Air Receiver) in strict accordance with ASME Boiler and Pressure Vessel Code (BPVC) Section VIII, Division 1, Mandatory Appendix 2. The analysis uses PVElite 2008 software with full manual verification of all key calculations.

The methodology follows the Waters-Rossheim-Wesstrom-Williams procedure codified in Appendix 2, which treats the integral weld neck flange as a structural ring under bending. The study covers gasket geometry, bolt load determination, flange moment calculation, stress component evaluation, rigidity index verification, and material qualification.

II. DESIGN SPECIFICATIONS AND INPUT DATA

A. Design Constraints

The heat exchanger operates under the following conditions established from the system process design:

Parameter	Value	Unit
Design Internal Pressure	6.895	bar
Design External Pressure	1.013	bar
Design Temperature	100	°C
Internal Corrosion Allow.	1.5	mm
External Corrosion Allow.	0	mm
Hydrotest Type	UG-99b	—
Design Code	ASME Sec. VIII Div. 1	2007

B. Flange Geometric Input Data

Parameter	Symbol	Value	Unit
Flange Type	—	Integral Weld Neck	—
Analysis Type	—	Partial Thickness	—
Flange Inside Diameter	B	1117.600	mm
Flange Outside Diameter	A	1325.000	mm
Flange Thickness	t	34.000	mm
Hub Thk. Small End	g_0	18.000	mm
Hub Thk. Large End	g_1	18.000	mm
Hub Length	h	50.000	mm
Bolt Circle Diameter	C	1230.000	mm
Nominal Bolt Diameter	d^B	24.000	mm
Number of Bolts	n	24	—
Flange Material	—	SA-516 Gr. 60	—
Bolt Material	—	SA-193 B7	—

III. THEORETICAL BACKGROUND

A. Weld Neck Flange Geometry

The weld neck flange features a tapered hub of length h transitioning from the small-end thickness g_0 at the pipe junction to the large-end thickness g_1 at the flange ring. This taper distributes bending stress and is the defining feature of the 'integral' flange classification in ASME Appendix 2. Key geometric parameters are:

Symbol	Parameter	Description
B	Bore Diameter	Equal to pipe ID
A	Outside Diameter	Outer edge of flange ring
t	Flange Thickness	Thickness at bolt circle
g_0	Small Hub Thk.	At pipe wall junction
g_1	Large Hub Thk.	At flange face junction
h	Hub Length	Axial length of taper
C	Bolt Circle	Bolt hole centreline

B. ASME Appendix 2 Methodology

The design procedure per ASME Appendix 2 treats the flange as a circular ring subjected to bending. The sequential steps are:

- Determine effective gasket width and gasket reaction diameter G
- Calculate hydrostatic end force (H), gasket contact force (Hp), and bolt loads (Wm1, Wm2)
- Determine flange moment arms (hd, ht, hg) and individual moments (Md, Mt, Mg)
- Derive shape factors F, V, f from ASME Fig. 2-7 based on hub geometry ratios h/h_0 and g_1/g_0
- Compute three stress components: longitudinal hub (SH), radial (SR), tangential (ST)
- Verify each stress against allowable and compute rigidity index $J \leq 1.0$

IV. DESIGN CALCULATIONS

A. Gasket Geometry (ASME App. 2-5)

Parameter	Formula	Result
Gasket Contact Width N	(Go−Gi)/2	31.200 mm
Basic Gasket Width b_0	N/2	15.600 mm
Effective Width b	$\sqrt{b_0/2}$ (b_0>6.3)	9.953 mm
Gasket Reaction Dia. G	Go−2b	1160.094 mm
Gasket Factor m	ASME Table 2-5.1	1.000
Seating Stress y	ASME Table 2-5.1	0.01 N/mm²

B. Bolt Load Calculations

Two governing load conditions are evaluated per Appendix 2-5:

Hydrostatic End Force:

```
H = 0.785 × G² × P
  = 0.785 × 1160.094² × 6.895
  = 74,315.945 Kgf
```

Gasket Contact Load:

```
Hp = 2bπGmP
   =
2×9.953×π×1160.094×1.0×6.895
   = 5,100.677 Kgf
```

Operating Bolt Load:

```
Wm1 = H + Hp = 74316 + 5101
    = 79,416.617 Kgf
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Gasket Seating Bolt Load:

```
Wm2 = ybπG =
0.01×9.953×π×1160.094
    = 25.892 Kgf
```

Required Bolt Area:

```
Am = max(Wm1/Sb, Wm2/Sa)
   = max(79416/172, 25/172)
   = 45.182 cm²
Ab (actual) = 75.060 cm² ✓ PASS
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C. Flange Moment Calculations

Moment	Force	Arm	Value
Md (End Pressure)	Hd=69,342 Kgf	hd=46.45 mm	3,221 Kg-m
Mt (Face Pressure)	Ht=4,974 Kgf	ht=44.83 mm	223 Kg-m
Mg (Gasket Load)	Hg=5,101 Kgf	hg=34.95 mm	178 Kg-m
Mop (Operating)	—	—	3,622 Kg-m
Matm (Seating)	W=105,674 Kgf	hg=34.95 mm	3,694 Kg-m

D. Flange Stress Equations (ASME App. 2-7)

Shape factors from ASME Figure 2-7: F=0.909, V=0.550, f=1.000, T=1.846, Y=11.674, Z=6.024, K=1.182. Stress factors: α=1.217, β=1.290, γ=0.659, λ=0.699.

Longitudinal Hub Stress (SH):

$$SHo = (f \times Mop/Bcor) / (L \times g_1^2) = (1.0 \times 3622/1120.6) / (0.699 \times 16.5^2) = 166.54\ N/mm^2 \leq 1.5 \times Sfo = 177\ ✓$$

Radial Flange Stress (SR):

$$SRo = (\beta \times Mop/Bcor) / (L \times t^2) = (1.290 \times 3622/1120.6) / (0.699 \times 32.5^2) = 55.36\ N/mm^2 \leq Sfo = 118\ ✓$$

Tangential Flange Stress (ST):

$$STo = (Y \times Mo/(t^2 \times Bcor)) - Z \times SRo = (11.674 \times 3622/(32.5^2 \times 1120.6)) - 6.024 \times 55.36 = 16.80\ N/mm^2 \leq Sfo = 118\ ✓$$

Average Flange Stress (SA):

$$SAo = (SHo + \max(SRo, STo)) / 2 = (167 + \max(55,17)) / 2 = 110.95\ N/mm^2 \leq Sfo = 118\ ✓$$

E. Flange Rigidity Index (ASME App. 2-14)

Excessive flange rotation reduces gasket contact stress and causes leakage. ASME Appendix 2, Article 2-14 limits rotation via the dimensionless rigidity index J ≤ 1.0:

$$J = 52.14 \times M \times C\_fac \times V / (\lambda \times E \times g_0^2 \times h_0 \times Ki)$$

Seating condition: Js = 52.14×3693×9806.636×0.550 / (0.699×199955×16.5²×135.978×0.300) = 0.681 ≤ 1.0 ✓

Operating condition: J = 52.14×3622×9806.636×0.550 / (0.699×196094×16.5²×135.978×0.300) = 0.681 ≤ 1.0 ✓

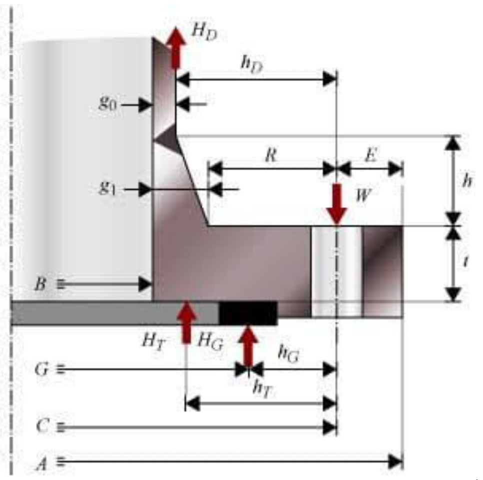
Both rigidity indices equal 0.681, well within the limit, confirming adequate rotational stiffness.

V. PVELITE SOFTWARE MODEL AND RESULTS

A. 3D Model and Design Constraints

The AEM Heat Exchanger was modelled in PVElite 2008. The Channel Flange (Element 4 of 8) is visible at the left end of the exchanger shell. Fig. 1 shows the 3D model with applied design constraints.

Fig. 1. PVElite 3D model of AEM Heat Exchanger — Channel Flange highlighted. Internal Pressure = 6 bar, Temperature = 80°C, Flange ID = 1117.6 mm, Material SA-516 60



B. Flange Input Data in PVElite

Fig. 2 shows the complete flange input as entered in PVElite, confirming the Integral Weld Neck classification with Partial Thickness analysis and all geometric parameters consistent with Table II above.

C. Hub Thickness and Corroded Dimensions

After applying the internal corrosion allowance of 1.5 mm, corroded dimensions are used in all calculations. Fig. 3 shows the hub thickness verification per UG-27(c)(1), gasket width calculations, and flange/bolt loads.

D. Bolting Information

Fig. 4 confirms that the actual bolt area Ab = 75.060 cm² exceeds the required Am = 45.182 cm² by a margin of 66%. TEMA bolt spacing requirements are also satisfied.

E. Flange Moments and Shape Factors

Fig. 5 shows the complete moment summary and ASME Fig. 2-7 shape factors computed by PVElite. Mop = 3622 Kg-m and Matm = 3694 Kg-m govern the operating and seating checks respectively.

F. Stress Computation Results

Fig. 6 shows all four stress components for operating and seating conditions. All are within the ASME allowable limits for SA-516 Grade 60.

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G. Flange Rigidity Indices

Fig. 7 shows the rigidity index calculations confirming $J = 0.681 \leq 1.0$ under both conditions. The MDMT of −29°C is well below the design temperature of 80°C; no impact testing is required per UCS-66.

VI. MATERIAL PROPERTIES

A. Flange Material — SA-516 Grade 60

Property	Value
Specification	SA-516 / ASTM A516
Min. Tensile Strength	415 N/mm²
Min. Yield Strength	220 N/mm²
Allowable Stress (Sfo)	117.90 N/mm²
Modulus of Elasticity	196,094 N/mm²

Property	Value
Max. Design Temperature	455 °C
Impact Testing (UCS-66)	Exempt above −29°C
Weldability	Good — low C equivalent

B. Bolt Material — SA-193 Grade B7

Property	Value
Specification	SA-193 / ASTM A193
Grade	B7 (Cr-Mo alloy steel)
Min. Tensile Strength	860 N/mm²
Min. Yield Strength	724 N/mm²
Allowable Stress (Sb)	172.38 N/mm²
Max. Operating Temp.	427 °C
Thread Type	TEMA Metric M24×3.0
Nut Material	SA-194 Grade 2H

VII. RESULTS AND DISCUSSION

Table VI summarises the complete ASME code compliance verification for all stress and geometric checks. Every parameter passes its respective code criterion, confirming that the channel flange is designed correctly for the specified service.

TABLE VI. Complete ASME Code Compliance Summary

Check	Actual	Allowed	Clause	Result
Min. Flange Thk.	32.36 mm	34.0 mm	App.2-3	✓ PASS
SHo (Hub, Oper.)	167 N/mm²	177 N/mm²	App.2-7	✓ PASS
SHa (Hub, Seat.)	170 N/mm²	177 N/mm²	App.2-7	✓ PASS
SRo (Radial, Op.)	55 N/mm²	118 N/mm²	App.2-7	✓ PASS
SRa (Radial, Se.)	56 N/mm²	118 N/mm²	App.2-7	✓ PASS
STo (Tang., Op.)	17 N/mm²	118 N/mm²	App.2-7	✓ PASS
STa (Tang., Se.)	17 N/mm²	118 N/mm²	App.2-7	✓ PASS
SAo (Avg., Op.)	111 N/mm²	118 N/mm²	App.2-7	✓ PASS
SAa (Avg., Se.)	113 N/mm²	118 N/mm²	App.2-7	✓ PASS

Check	Actual	Allowed	Clause	Result
BSo (Bolt, Op.)	104 N/mm²	172 N/mm²	App.2-5	✓ PASS
Bolt Area Ab/Am	75.06 cm²	45.18 cm²	App.2-5	✓ PASS
Rigidity Js	0.681	≤1.0	App.2-14	✓ PASS
Rigidity J	0.681	≤1.0	App.2-14	✓ PASS
MDMT (UCS-66)	−29°C	80°C design	UCS-66	✓ PASS
MAWP (Operating)	7.3 bar	≥6.0 bar	App. 2	✓ PASS
MAWP (Seating)	7.7 bar	≥6.0 bar	App. 2	✓ PASS

The following observations are drawn from the results:

- The flange thickness margin is 5.1% (34 mm provided vs 32.36 mm required), indicating a lean but fully compliant design.
- The bolt area margin of 66% (Ab/Am = 75.06/45.18) provides substantial reserve capacity for bolt load variability during assembly.
- Longitudinal hub stress (SHo = 167 N/mm²) is the most critical stress, utilising 94.4% of its allowable. This is expected for an integral weld neck flange under internal pressure.
- Tangential and radial stresses are well below allowable, reflecting the conservative integral flange geometry.
- The rigidity index J = 0.681 is 32% below the unity limit, confirming no rotation-induced leakage risk.
- The MAWP of 7.3 bar provides a 21.7% pressure margin above the 6.0 bar design pressure, satisfying pressure relief and upset condition requirements.

VIII. CONCLUSIONS

The complete design and analysis of the circular weld neck forged flange (Channel Flange, AEM HE:1) has been performed in full conformance with ASME BPVC Section VIII, Division 1, Appendix 2. The following conclusions are established:

1. Design Adequacy: The SA-516 Grade 60 weld neck flange is structurally adequate for the specified gas pipeline service. All sixteen ASME code checks pass.

2. Thickness: Provided thickness of 34 mm exceeds the minimum required 32.36 mm (5.1% margin). Hub required thickness of 4.79 mm is met by the 18 mm provided hub.

3. Bolt Design: The 24 × M24 SA-193 B7 bolts provide an area margin of 66% over the ASME minimum, ensuring robust sealing under all load conditions.

4. Flange Rigidity: The rigidity index J = 0.681 for both operating and seating conditions is well below the ASME limit of 1.0, confirming adequate stiffness against rotation-induced leakage.

5. MAWP: The Maximum Allowable Working Pressure of 7.3 bar exceeds the 6.0 bar design pressure by 21.7%, providing a safe operating envelope.

6. MDMT: No impact testing is required; the SA-516 Grade 60 material is exempt per ASME UCS-66 at the design temperature of 80°C.

7. Code Compliance: The design is in full compliance with ASME Section VIII, Division 1 and is fit for intended service.

Recommendations

- Verify gasket contact width with supplier: actual width 31.2 mm is marginally below the Brownell–Young recommended 32 mm (non-mandatory).
- Prepare a bolt tightening procedure for 24×M24 SA-193 B7 studs specifying torque values for uniform gasket seating.
- Specify gasket seating surface finish per ASME B16.20 (typically Ra 125–250 for spiral wound gaskets).
- Perform volumetric examination (RT or UT) of weld neck hub-to-shell weld per ASME UW-11.

IX. REFERENCES

[1] ASME Boiler and Pressure Vessel Code (BPVC), Section VIII Division 1, 2007 Edition. American Society of Mechanical Engineers, New York, USA.

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[3] ASME Section II, Part D, “Material Properties — Allowable Stresses,” 2007.

[4] ASME B16.5, “Pipe Flanges and Flanged Fittings,” 2017. American Society of Mechanical Engineers.

[5] ASME B16.20, “Metallic Gaskets for Pipe Flanges,” 2017.

[6] TEMA Standards, 10th Edition, 2019. Tubular Exchanger Manufacturers Association, New York.

[7] E.O. Waters, D.B. Rossheim, D.B. Wesstrom, F.S.G. Williams, “Development of General Formulas for Bolted Flanges,” Taylor Forge and Pipe Works, 1949.