Document Title	API618 DA2 Study of N2 and Air Compressor Skids
DRG Document No.	DRG-101872-2829-RP01-R00
Client	Airpack Nederland BV.
Project	API 618 Design Approach 2 for 17811-OO-0701

DYNAFLOW RESEARCH GROUP.

API618 DA2 Study of N2 and Air Compressor Skids

0	Issued for comments	For Comments	TK	MPB	FMB	18/02/'22
Rev.	**Description**	**Status**	**Prep'd**	**Chk'd**	**App'd**	**Date**

CONFIDENTIAL

This document is made available subject to the condition that the recipient will neither use nor disclose the contents except as agreed in writing with the copyright owner. Copyright is vested in Dynaflow Research Group B.V., Rijswijk (ZH).

Neither the whole nor any part of this document may be reproduced or distributed in any form or by any means (electronic, mechanical, reprographic, recording or otherwise) without the prior written consent of the copyright owner.

Dynaflow Research Group B.V. has made every effort to ensure that the interpretations, conclusions and recommendations presented herein are accurate and reliable in accordance with good industry practice and our quality management procedures.

Dynaflow Research Group B.V. does not however guarantee the correctness of any such interpretation and shall not be held liable or responsible for any loss, costs, damages or expenses incurred or sustained by any resulting from any interpretation or recommendation made by any of our officers, agents or representatives.

List of Contents

EXECUTIVE SUMMARY

This report describes the results of the pulsation and vibration analysis conform API 618 Design Approach 2 for two reciprocating compressor systems designed by Airpack for the purpose of compressing nitrogen (system 17811-03A) and air (system 17811-03B). The applicable system was modeled using the pulsation and vibration analysis software BOSpulse v4.2.

The complete system of skid and interconnecting piping complies with the requirements of API 618 Design Approach 2 if the following recommendations were implemented in the piping connected to the compressor skid. One exception is the maximum pulsation at the compressor flange, which was found at 103% for the 1st stage compressor's discharge flange. Airpack indicated that a 3% excess is within their margin.

In order to have the system comply with the requirements of the separation margin, the lower mechanical natural frequencies of the connected piping need to be eliminated by additional supports. A layout for the support arrangement was presented on marked-up isometrics as provided in Appendix B.

1. Introduction

This report contains the results of the pulsation and vibration analysis as per API 618 Design Approach 2 for the reciprocating compressor systems designed by Airpack for the purpose of compressing nitrogen and air. The applicable system was modeled using the pulsation and vibration analysis software BOSpulse v4.2.

Section 2 includes an overview of all modelling data used for the analysis. Section 3 describes the methodology for conducting the API 618 Design Approach 2 study. Section 4 shows the result of the study and Section 5 closes the report with final conclusions and recommendations.

2. System Data

The pulsation analysis has been performed using the software package BOSpulse v4.2.

2.1. Model details

2.1.1. Nitrogen compressor skid 17811-03A

The Nitrogen compressor system consists of the following components or parts:

- Two-stage compressor. Each stage consists of a single throw. All throws are double acting.
- Compressor is driven by a fixed speed motor running at 400 RPM (6.7 Hz).
- Each suction and discharge stage is outfitted with its own Pulsation Suppression Device (PSD).
    - 20-DC-1002-1: 1st stage suction PSD consists of a single volume "vessel" with 12″ diameter and approximately 1300 mm in length.
    - 20-DC-1002-2: 1st stage discharge PSD consists of a single volume "vessel" with 12″ diameter and approximately 1230 mm in length.
    - 20-DC-1002-3: 2nd stage suction PSD consists of a single volume "vessel" with 10″ diameter and approximately 805 mm in length.
    - 20-DC-1002-4: 2nd stage discharge PSD consists of a single volume "vessel" with 10″ diameter and approximately 1000 mm in length.
- A cooler is located downstream of each stage (20-AEC-1002-1 and 20-AEC-1002-2).
- The compressor is fed by a nitrogen generation package and discharges to vessel 20-DC-1002-1.

The pulsation model is created in BOSpulse v4.2 and contains all relevant piping in which pulsations are present. An overview of the model is shown in Figure 1.

A detailed overview of the model is submitted with this report in the form of a BOSview file attached to Appendix A.

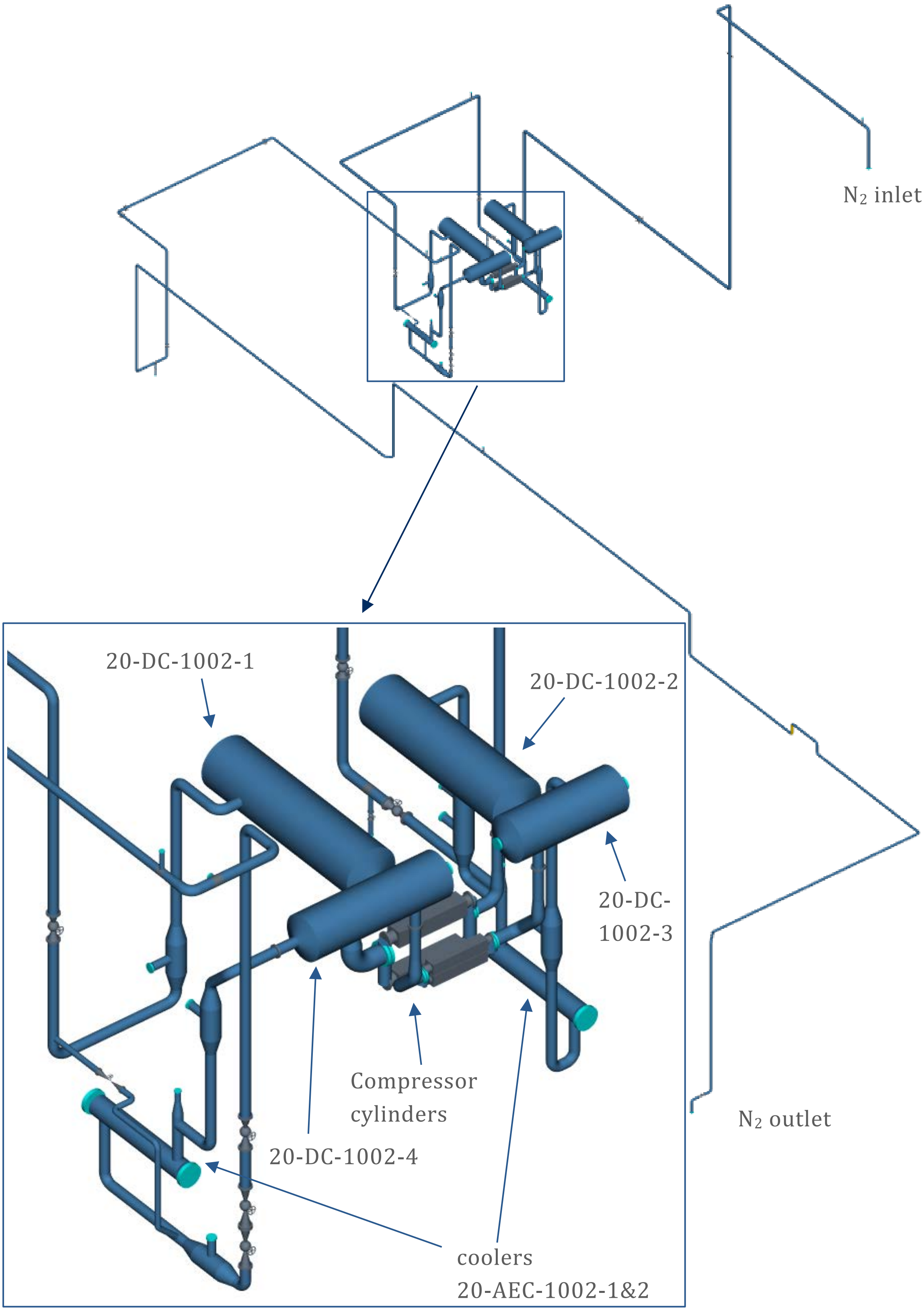

Figure 1: Overview of the N2 compressor (17811-03A) model.

2.1.2. Emergency Air compressor skid 17811-03B

The Emergency Air compressor system consists of the following components or parts:

- Single-stage compressor. The single stage consists of two throws. Each throw is single acting.
- Compressor is driven by a fixed speed motor running at 400 RPM (6.7 Hz).
- The compressor is outfitted with pulsation suppression devices (PSD) on the discharge and suction sides.
  - 20-DC-7080-1: suction PSD consists of a single volume "vessel" with 8″ diameter and approximately 850 mm in length.
  - 20-DC-7080-2: discharge PSD consists of a single volume "vessel" with 8″ diameter and approximately 850 mm in length.
- A cooler is located downstream of the discharge PSD (20-AEC-7080-1).

An overview of the model is shown in Figure 2.

A detailed overview of the model used is submitted with this report in the form of a BOSview file attached to Appendix A.

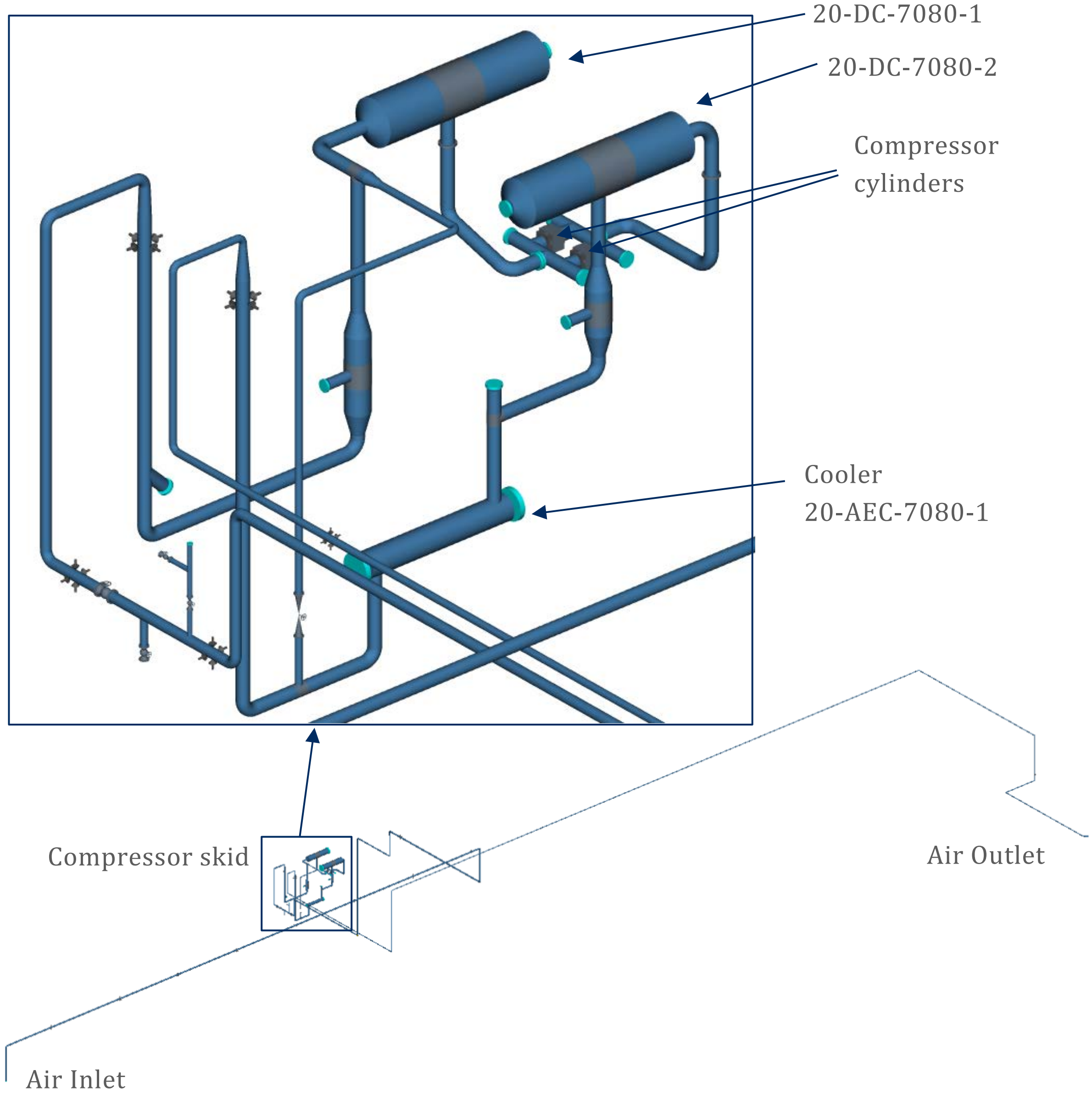

Figure 2: Overview of the Air Compressor (17811-03B) model.

2.2. Boundary conditions

The boundary conditions for the pulsation analysis are based on the information on the P&ID's, see Appendix G .

For the Nitrogen compressor the boundary conditions are defined as:

- A fixed pressure at the N_2 inlet of 8 bara.
- A fixed pressure at the outlet of 24 bara.

For the air compressor the boundary conditions are defined as:

- A fixed pressure at the air inlet of 8 bara.
- A fixed pressure at the outlet of 21 bara.

2.3. Load cases

The compressor system has one single mode of operation. This mode of operation is analyzed, variations to include uncertainty in gas temperatures have been calculated as well. The temperature variation is considered around a based temperature profile bounded by the cold and hot cases.

An overview of the temperature variations is shown in Table 1 and Table 2.

Table 1: Temperature ranges studied for the N_2 compressor skid.

		base	cold	hot
T11 : N2 inlet – stage1 compressor	°C	52	27	72
T12 : stage 1 compressor – inter cooler	°C	134	109	154
T21 : inter cooler – Stage 2 compressor	°C	50	25	70
T22 : Stage 2 compressor – aftercooler	°C	64	39	84
T3 : aftercooler – outlet of skid	°C	40	15	60

Table 2: Temperature ranges studied for the emergency air compressor skid.

		base	cold	hot
T1 : air inlet – compressor	°C	30	5	50
T2 : compressor – after cooler	°C	180	155	200
T3 : aftercooler – outlet of skid	°C	40	15	60

The temperature inside the coolers is modelled at the average of the temperature in the piping upstream and downstream of the cooler.

2.4. Gas properties

The AGA-8 gas model was used to determine the relevant properties of the nitrogen in the simulations of the nitrogen compressor skid.

For the air compressor an ideal gas was used to model the fluid properties of air.

2.5. Component settings

2.5.1. Reciprocating compressors

The parameters defining the reciprocating compressors are shown in Table 3.

Table 3: Compressor characteristics of both compressor systems.

		N_2 compressor		Air Compressor
		1st stage	2th stage	-
# cylinders		1	1	2
Speed	rpm	400	400	400
SA/DA		Double acting	Double acting	Single Acting
Piston diameter	mm	160	100	90
Crank arm radius	mm	70	70	70
Con rod length	mm	350	350	350
Clearance Volume HE	%	0.69	0.69	0.69
Clearance Volume CE	%	0.62	0.62	-

2.5.2. Pulsation Suppression Devices (PSD's)

Each suction and discharge stage is outfitted with its own pulsation suppression device (PSD). All PSDs are single volume bottles without any internals.

3. METHODOLOGY

3.1. API 618 Design Approach 2

The analysis criteria for the current study are based on API 618 (5th ed. 2007) Approach 2 as detailed in 7.9 and Annex M Figure M-3 of the standard. The related checks that have been performed are the following:

- Maximum Allowable Pulsation Limits at and Beyond Line-side Nozzles of Pulsation Suppression Devices (7.9.4.2.5.2.2.2)
- Maximum allowable compressor cylinder flange pressure pulsation (7.9.4.2.5.2.2.1)
- Maximum Allowable (non-resonant) Acoustic Shaking Force on PSD (7.9.4.2.5.2.3)
- Maximum Allowable (non-resonant) Acoustic Shaking Force on piping (7.9.4.2.5.2.3)
- Maximum Allowable Pressure Drop (7.9.4.2.5.3.1)
- Separation margin criteria (7.9.4.2.5.3.2)

3.1.1. Check on Pressure amplitudes (7.9.4.2.5.2.2) - Piping

Downstream or upstream of the pulsation bottle exit flange the periodic pulsation amplitudes (peak to peak) will be decomposed in harmonics and subsequently checked for conformance with the limits in API 618 section 7.9.4.2.5.2.2.2 Eq. 8 and shown here as Eq. 3-1.

$$P_1 = \sqrt{a/350}\left(\frac{400}{(P_L D_1 f)^{0.5}}\right) \qquad 3\text{-}1$$

Where:

P_1 is the allowable pressure amplitude peak to peak [% of P_L] for the applicable harmonic frequency,

a [m/s] is the speed of sound,

P_L [bara] is the average line pressure,

D_1 [mm] is the inside dia. of the applicable pipe,

f [Hz] is the harmonic frequency of the pulsation component.

The periodic pressure time histories are analyzed at the harmonics of the compressor running speed which are determined as shown in Eq. 3-2. The pressure amplitude at each harmonic being found by a discrete Fourier decomposition of the periodic pressure signal.

$$f = \frac{N \cdot z}{60} \qquad 3\text{-}2$$

Where:

N [rpm] is the compressor running speed [rpm]

z [-] is the harmonic number, i.e. 1, 2, 3, etc.

3.1.2. Check of Pressure amplitudes (7.9.4.2.5.2.1) – Compressor Cylinder Flange

The pulsation amplitudes at the compressor cylinder flange will be checked for conformance with the limits in API 618 section 7.9.4.2.5.2.1 Eq. 6 and shown here as Eq. 3-3. Where R is the stage pressure ratio and P_{cf} is the allowable pressure amplitude (peak to peak) as % of the average line pressure.

$$P_{cf} = \min(3R\%, 7\%) \qquad 3\text{-}3$$

The main objective of this check is to verify the pulsations on the compressor valves in an attempt to ensure a minimum level of performance and life time of the valves.

3.1.3. Pressure drop criteria (7.9.4.2.5.3.1)

The maximum allowable pressure drop (ΔP) over the PSD's including any restricting orifice.

$$\Delta P = \max\left(1.67\left(\frac{R-1}{R}\right)\%, 0.25\%\right)\ of\ P_L \qquad 3\text{-}4$$

Where R is the stage pressure ratio and P_L is the mean absolute line pressure at the device.

3.1.4. Non-resonant shaking force criteria (7.9.4.2.5.2.3)

The shaking forces arising in the piping are checked against the lowest of 3-5 and 3-6. The shaking forces arising on the PSD's are checked against the lowest of 3-5 and 3-7.

$$SF_k = k_{eff} \times V \qquad 3\text{-}5$$

$$SF_{pmax} = 45 \times NPS \qquad 3\text{-}6$$

$$SF_{dmax} = 45000\ \text{N} \qquad 3\text{-}7$$

Where SF [N] is the shaking force, V is the design vibration peak-to-peak guideline, NPS [mm] is the nominal pipe size and k_{eff} is the effective static stiffness given by Eq. 3-8 where k_s is the static stiffness.

$$k_{eff} = 0.66 \times k_s \qquad 3\text{-}8$$

All shaking force criteria only apply to forces for which the frequency is sufficiently separated from the frequency of the mechanical eigenmodes of the system.

3.1.5. Separation margin criteria (7.9.4.2.5.3.2)

To verify that the shaking forces in the system are not causing resonance, meaning there is no overlap between the mechanical and acoustical resonance frequencies, either the mechanical natural frequency needs to be above 2.4 times the maximum rated speed of the compressor or it needs to be checked that there is a separation of +/-20% as per API 618 7.9.4.2.5.3.2.

A combination of two methods was used for the determination of sufficient separation margin. The first method applies to full restraining i.e., using clamped supports at each support location. The second method applies to restraint principles using supports with well-defined support functionality such as axial stops, guides and rest + hold-down supports.

For the first method, API 688 (2012) was used to calculate a span table for the system. API 688 (2012) section 3.2.7.2 describes the Fundamental Analytical Method (FAM). The

Fundamental Analytical Method (FAM) uses beam formulas for typical piping sections. This method only applies to piping sections of low complexity with sufficient clamps near bends and concentrated masses. The outcome is a piping span table with criteria for the minimum required pipe support spans.

The second method, is applicable for systems with well-defined support functionalities. In this method the mechanical natural frequencies are calculated using Finite Element Analysis and includes the support stiffness. Only mechanical natural frequencies that can be excited by the axially oriented shaking forces will be considered in this analysis.

Finally, for the PSDs, a combination of the axial stiffness with the mass of the PSD was used to conservatively determine the lowest mechanical natural frequency.

4. Results and Discussion

All results computed including pulsations levels and shaking forces are shown in the BOSview file in Appendix A. The first 12 harmonics were resolved and evaluated for the system.

4.1. Pulsation check compressor cylinder flange

It was found that the maximum pulsations at the compressor cylinder flange were within allowable values for most of the cases studied. In the N_2 system (17811-03A) the 1st stage compressor experiences pulsations that amount to 103% of the allowable pulsation levels. The goal of this criterium is to ensure compressor valve life time and compressor efficiency. The valve dynamics in combination with pulsations will determine reduced efficiency. Airpack has indicated that this excess is within their allowable margin.

The maximum pulsations at the cylinder flanges of the air compressor (17811-03B) were within the allowable values for all cases studied.

A complete overview of all pulsations at the compressor flange is included in Appendix E.

4.2. Pressure drop criteria

Maximum pressure drop over the pulsation suppression devices were all within allowable values for both systems and all cases studied.

A complete overview of the pressure drop assessment for all cases is given in Appendix D.

4.3. Pulsation check beyond Line-side Nozzles of Pulsation Suppression Devices

A pre-study has been performed following API 618 Design Approach 2, in which the initial dampener check has been performed. The analysis in this report is carried out using the redesigned skid layouts that followed from the pre-study.

An additional orifice plate is required at the exit nozzle of the stage 2 discharge PSD (42mm ID) in order to reduce line-side pulsations. With the addition of this orifice plate, pulsations beyond the line-side nozzles of the pulsation suppression devices are within the allowable values throughout both systems. An overview of the maximum relative pulsations in the system is shown in Figure 3 for the N_2 compressor system and Figure 4 for the emergency air compressor system.

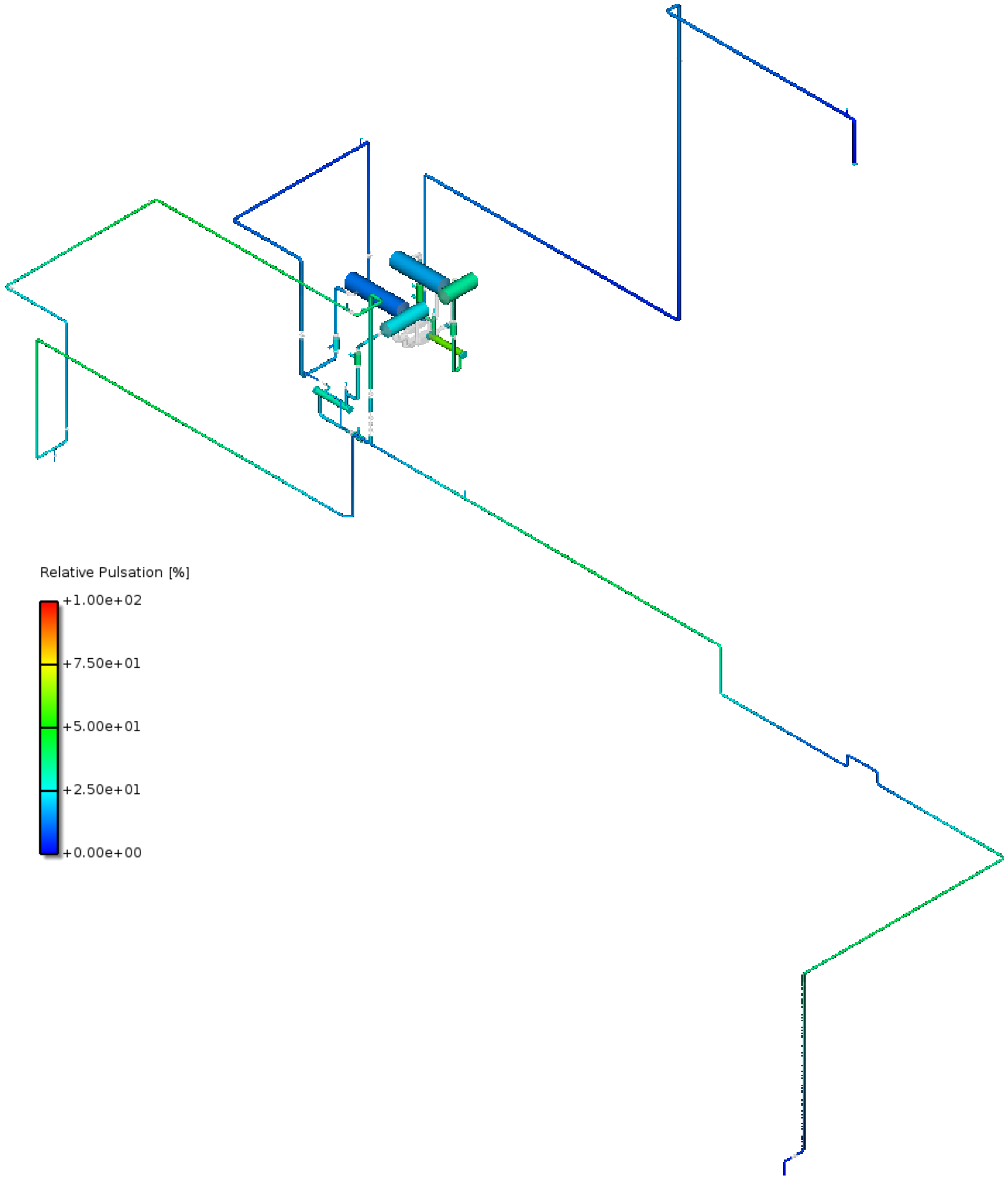

Figure 3: Maximum relative pulsation in the N_2 compressor system

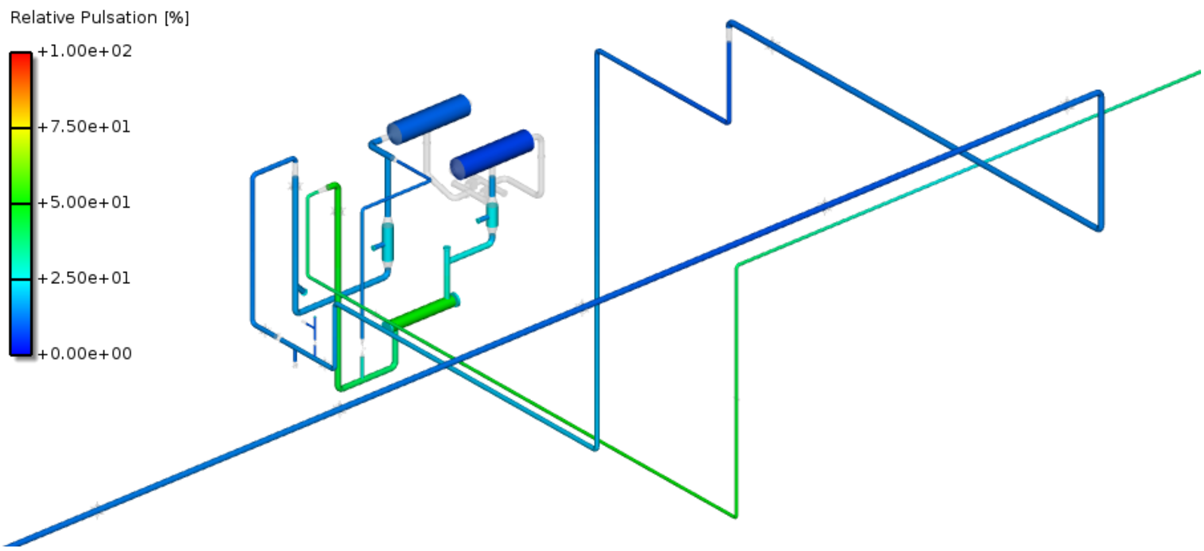

Figure 4: Maximum relative pulsation in the air compressor system.

A complete overview of the pulsations for all cases throughout the system is given in Appendix A.

4.4. Maximum Allowable (non-resonant) Acoustic Shaking Force

The maximum non-resonant acoustic induced shaking force is exceeded in two locations for the N_2 compressor system.

The first location is a small section of piping (1'') just upstream of the Pressure Safety Valve between the 1st and 2nd stage compressors. The analysis and allowable values are based on shaking forces acting on long straight sections of piping. Such a short element that is in line with a larger bore line is therefore exempt from the acoustic shaking force check. No action is required following this check.

The other location where the acoustic shaking force checks fails is in the off-skid piping. One piping section has a length which matches with the 2nd harmonic of the acoustic system. A proposal is made to introduce an expansion loop in this section, which is indicated in Appendix B. When the expansion loop is introduced, the maximum non-resonant shaking forces are within the allowable values. The highest value for the relative shaking force occurs on-skid, with a value of 94.1%. The maximum relative shaking forces are shown in Figure 5. The added expansion loop is encircled.

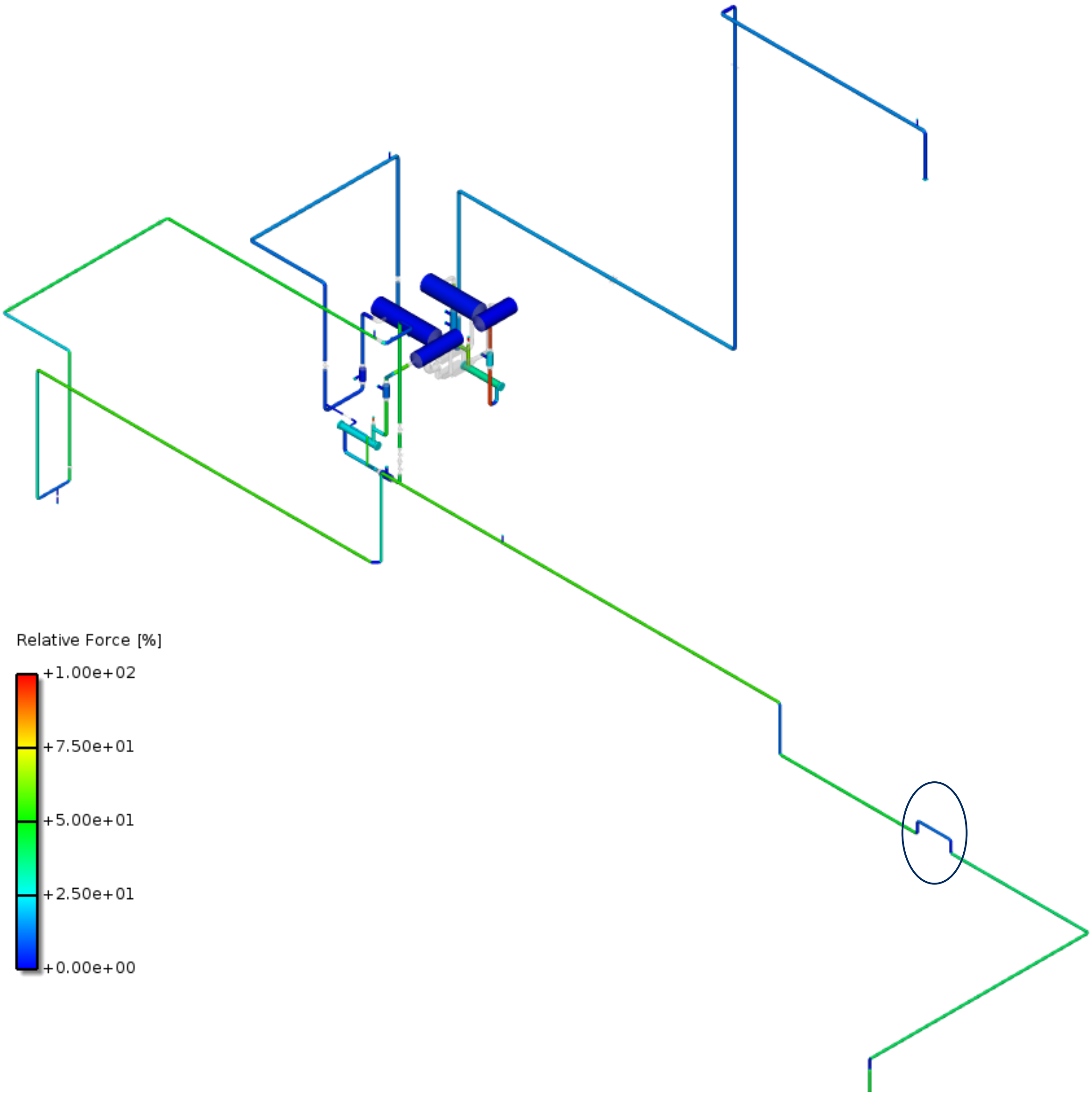

Figure 5: Maximum relative non-resonant shaking force in the N_2 compressor system.

For the Air compressor system, the Maximum acoustic induced shaking forces exceeded the allowable values in a small section of off-skid piping. A reducer (2'' to 1'') is located right above the skid outlet flange. Similar to the location downstream of the PSV discussed before, the excess of such a small section of piping can be left as is. By relocating this reducer to after the first bend, the shaking forces are brought within the allowable values throughout the system both for the PSDs and the piping. The relocation of the reducer is indicated in Figure 6.

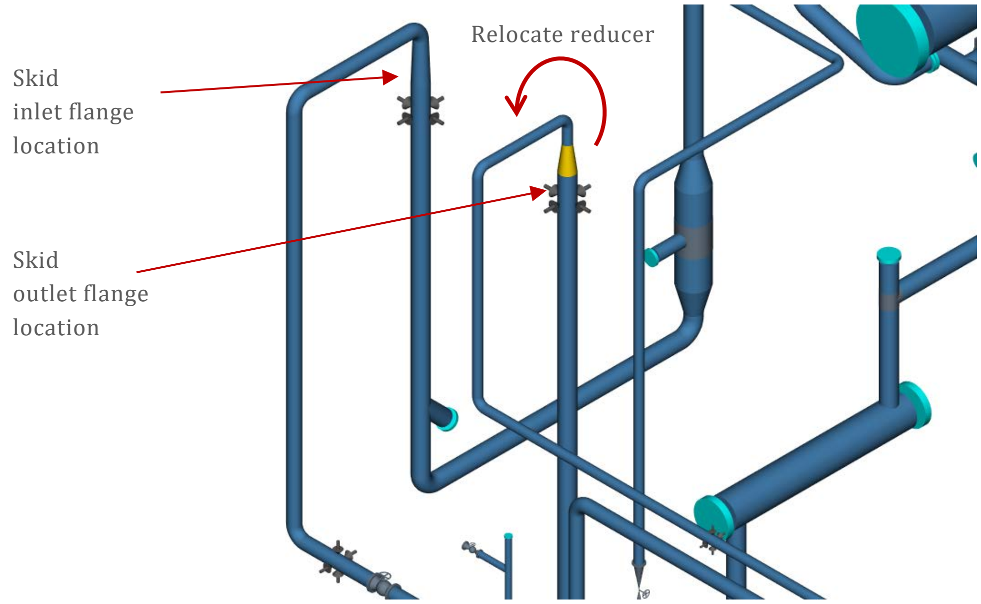

Figure 6: Relocate reducer (highlighted yellow) at outlet piping to beyond the next bend.

This is also shown in Figure 7 for the emergency air compressor system. The highest calculated relative non-resonant shaking force in the air compressor system, after moving the reducer, is 90.5%.

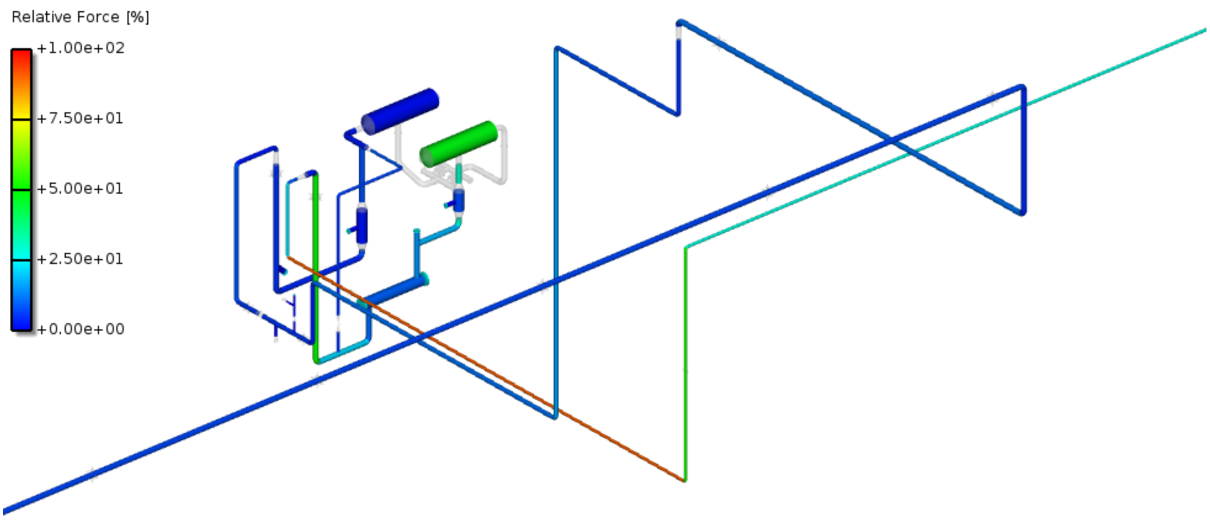

Figure 7: Maximum relative non-resonant shaking force in the Air Compressor System.

Details of all shaking forces calculated for all cases throughout the system is given in Appendix A.

4.5. Separation margin criteria

For the acoustic shaking forces to be non-resonant, the mechanical natural frequencies should be higher than 2.4 times the running speed of the compressor. For these systems, which run at the same speed, the minimum mechanical natural frequency should therefore be 32 Hz.

For the on-skid piping, a span table is created and attached to Appendix C. All on skid supporting is based on these span tables and presented in Appendix F.

The mechanical natural frequency of the PSDs was calculated to be 60 Hz or higher.

For the remaining piping of the air compressor system, a modal analysis was conducted using the BOSpulse interface with Ansys. For the initial design, several excitable mechanical modes below 32 Hz were identified due to a lack of restraints in the system. Therefore, recommendations are made for addition of supports in order to increase the lowest mechanical natural frequencies. The recommendations are marked-up on the isometrics in Appendix B.

5. Conclusions and Recommendations

In the present report the results were described for the pulsation study of the N2 compressor system (17811-03A) and the emergency air system (17811-03B). The conclusions for both systems based on the previously described results can be found below.

5.1. Conclusions for N2 compressor system (17811-03A)

It was found that the N2 compressor system (17811-03A) exceeds the allowable pressure on the compressor flange of the 1^{st} stage discharge. The pulsations were shown to exceed the allowable value by 3%, the client (Airpack) has indicated that this is within an allowable margin and therefore accepable. A modification to the off-skid piping is recommended to reduce the maximum shaking forces. This modification is the introduction of an expansion loop.

5.2. Conclusions for emergency air system (17811-03B)

The complete emergency air system (17811-03B), including both the skid and the interconnecting piping complies with the requirements of API 618 Design Approach 2 if the recommendations for support arrangement are implemented in the piping connected to the compressor skid.

5.3. Recommendations

- For both systems the recommended pipe support arrangement is provided in the marked-up isometrics in Appendix B. With these recommendations implemented the system API 618 design approach 2 pulsations requirements are met. The recommended modifications all increase the minimum mechanical natural frequencies.
- An additional orifice plate should be installed at the exit nozzle of PSD 20-1002-4, with an inner diameter of 42mm to bring line-side pulsations within allowable levels.
- An expansion loop should be installed in the off-skid discharge piping of 17811-03A to reduce the maximum shaking force.

APPENDICES

DYNAFLOW RESEARCH GROUP.

Head Office

Laan van Oversteen 20
6th floor
2289 CX Rijswijk ZH
The Netherlands
+31 (0)85 058 00 46

Reg. no. 27320315

Middle-East Office

Bay X2 Tower, unit 3109
Jumeirah Lake Towers, cluster X
P.O. Box 73001, Dubai
United Arab Emirates
+971 (0)4 447 4479

DMCC license no. JLT-67987

info@dynaflow.com
www.dynaflow.com