Viking Sky Investigation

Report for: Fleet Services Manager

Name of client: Lloyd's Register Group Limited

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Summary

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Document control

Revision history

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0.1	03-APR-2023	Issued internally for review
1.0	14-APR-2023	First issue of report

List of abbreviations

Abbreviation	Description
AIBN	Accident Investigation Board Norway (now NSIA)
AIS	Automatic Identification System
CFD	Computational Fluid Dynamics
DAD	Design Appraisal Document
DoF	Degree of Freedom
EEDI	Energy Efficiency Design Index
IACS	International Association of Classification Societies
IPR	Intellectual Property Rights
JONSWAP	Joint North Sea Wave Project
LR	Lloyd's Register
MAIB	Marine Accident Investigation Branch
MAST	Marine Asset Survey Tool
MSC	Maritime Safety Committee
NMA	Norwegian Maritime Authority
NSIA	Norwegian Safety Investigation Authority (formerly AIBN)
OEM	Original Equipment Manufacturer
SINTEF	SINTEF Ocean AS
SOLAS	International Convention for the Safety of Life at Sea
TA	Lloyd’s Register Type Approval System
UI	Unified Interpretation
UR	IACS Unified Requirement
USCG	United States Coast Guard
UTC	Coordinated Universal Time
VoF	Volume of Fluid

Executive summary

This report summarises Lloyd's Register's internal investigation into the loss of propulsion incident suffered by MV Viking Sky on 23rd March 2019 under adverse weather conditions. The extant interim investigation report for the incident, published by the Norwegian accident investigators (NSIA), attributes the loss of propulsion to engine lubricating oil failure as a result of operating the engines with sump tank lubricating oil levels significantly below those recommended by the engine manufacturer. Such a finding has generally been acknowledged by all stakeholders.

The investigation established that applicable governing requirements were considered satisfied by LR. It is acknowledged that the underlying requirements relating to the static and dynamic inclinations to be satisfied in SOLAS Reg. II-1, 26.6 are open to interpretation, as became apparent, in discussions with the NSIA as part of their ongoing investigation. Recognising the potential for differing interpretations of the requirements, extensive detailed modelling of the performance of the MV Viking Sky lubricating oil sump tank number 5, was undertaken by LR as part of the investigation. Modelling analysed the performance of the sump tank when subject to both static inclinations, partially (but not fully) defined in the aforementioned SOLAS requirement, and also dynamic inclinations (irregular motions), when subject to representative adverse weather conditions. Additionally, review of LR's fleet database revealed no incidents of lubricating oil failure due to operation under adverse weather conditions.

Following internal investigation LR concludes that its Rules and Regulations were considered satisfied at the time of build of MV Viking Sky and, as such, the design of the lubricating oil sump tanks is acceptable to LR. The absence of incidents of lubricating oil failure attributable to operation in adverse conditions further supports such a conclusion.

The investigation into the MV Viking Sky incident has identified that information necessary to fully define the dynamic inclinations in SOLAS Reg. II-1, 26.6 is missing from the regulation and, as such, its application, and the application of the associated Classification requirements, is open to differing interpretations by Flag Administrations, Classification Societies, and the industry generally. LR therefore recommends that all stakeholders involved in the MV Viking Sky investigation cooperate in bringing this to the attention of the IMO in order to provide clarity and facilitate a harmonised application of the requirement across the maritime industry.

Contents

Viking Sky Investigation

1. Introduction

This report summarises LR's internal investigation into the incident experienced by Viking Sky, IMO 9650420, on 23rd March 2019, during a South-westerly passage to Bodø, off the Norwegian coast[1].

Information presented within this report relate to investigation into performance of lubricating oil tank number 5, positioned starboard on the asset (Master List item 7975, LR MAST application) with respect to governing Statutory and Classification requirements of the asset. The identified lubricating oil tank has been chosen for analysis based upon initiation of incident as recorded for diesel generator number 4 (Master List item 424, LR MAST application). The same lubricating oil tank has been the subject of investigation by Norwegian Safety Investigation Authority (NSIA).

Additionally, LR initiated a historical review of assets within its fleet (current and historical) for incidents that had been attributed to loss of propulsion due to low lubricating oil pressure shut-downs resulting from heavy weather, spanning over fifty-years, for all asset types.

During the investigations and discussions, LR has also undertaken an opportunity to conduct CFD analysis of the lubricating oil tank, which is over and above the normal Statutory and Classification certification and approval process.

1.1 Ship's particulars

IMO Number	9650420
Asset Flag	Norway (NIS)
Port of Registry	Bergen
Asset Name	VIKING SKY
Keel Laying Date	20-Dec-2013
Date of Build	26-Jan-2017
Overall Length, m	228.30
Length between perpendiculars, m	195.50
Builder	Fincantieri S.P.A Ancona
Yard Number	6237
Ship Type	Passenger / Cruise Ship
Registered Owner	Viking Ocean Cruises Ship II
Operator	Wilhelmsen Ship Management AS

Table 1.1 - Viking Sky particulars

1.2 Statutory requirements and classification rules

1.2.1 Statutory regulations

Statutory regulations which relate directly to the performance of the lubricating oil tank are, principally, related to operation under static or dynamic inclinations. The relevant regulations are contained within the SOLAS International Convention.

- Chapter II-1 - Construction - Substructure, subdivision and stability, machinery and electrical installations, Part C - Machinery installations, Regulation 26.6
  - Main propulsion machinery and all auxiliary machinery essential to the propulsion and the safety of the ship shall, as fitted in the ship, be designed to operate when the ship is upright and when inclined at any angle of list up to and including 15° either way under static conditions and 22.5° under dynamic conditions (rolling) either way and simultaneously inclined dynamically (pitching) 7.5° by bow or stern. The Administration may permit deviation from these angles, taking into consideration the type, size and service conditions of the ship

The following Statutory instruments are also considered of relevance

- SOLAS
  - Chapter II-2 - Construction - Fire protection, fire detection and fire extinction, Part B - Prevention of fire and explosion
    - Regulation 4.2 - Arrangements for oil fuel, lubrication oil and other flammable oils
- MARPOL – International Convention for the Prevention of Pollution from Ships
  - Annex VI, Chapter 4 Regulations on Energy Efficiency for Ships
    - Regulation 19 - Application
    - Regulation 20 - Attained Energy Efficiency Design Index (Attained EEDI)
    - Regulation 21 - Required EEDI
- Maritime Safety Committee (Circulars)
  - MSC/Circular.1053 - Explanatory Notes to the Standards for Ship Manoeuvrability - (Adopted on 16 December 2002)
- Maritime Safety Committee - Marine Environment Protection Committee Circulars
  - MSC-MEPC.2/Circ.11 Interim Guidelines for Determining Minimum Propulsion Power to Maintain the Manoeuvrability of Ships in Adverse Conditions – (3 December 2012)
    - Annex - Interim Guidelines for Determining Minimum Propulsion Power to Maintain the Manoeuvrability of Ships in Adverse Conditions
- Marine Environment Protection Committee (Resolutions)
  - Resolution MEPC.203(62) - Adopted on 15 July 2011

1.2.2 Classification rules

LR's applicable Classification Rules are determined upon the contract date between the main builder and the prospective owner, upon which LR's Rules and Regulations for the Classification of Ships, July 2012 were applicable.

- Part 1, Chapter 2 Classification Regulations
  - Section 5 Approval/Type Testing/Quality Control System
  - Section 5.1 LR Type Approval - Marine Applications

- Part 3, Chapter 7 Machinery Spaces - Section 6 Engine seatings
    - Section 6.1 General
    - Section 6.2 Seats for oil engines

- Part 4, Chapter 1 General Cargo Ships - Section 8 Double bottom structure
    - Section 8.2 Application
    - Section 1.2 Structural configuration

- Part 4, Chapter 2 Ferries, Roll on-Roll off Ships and Passenger Ships - Section 1 General
    - Section 1.1 Application
    - Section 1.2 Structural configuration
    - Section 1.3 Class notations
    - Section 1.4 Information required

- Part 4, Chapter 2 Ferries, Roll on-Roll off Ships and Passenger Ships - Section 2 Longitudinal strength
    - Section 1.1 Application
    - Section 1.2 Structural configuration
    - Section 1.3 Class notations
    - Section 1.4 Information required

- Part 4, Chapter 2 Ferries, Roll on-Roll off Ships and Passenger Ships - Section 6 Double bottom
    - Section 6.1 General

- Part 5, Chapter 1 General Requirements for the Design and Construction of Machinery
    - Section 3.7 Inclination of ship
        - Table 1.3.2 Inclination of ship (Partial table detail shown)

Installations, components	Angle of inclination, degrees *see* Note 1			
	Athwartships		Fore-and-aft	
	Static	Dynamic	Static	Dynamic
Main and auxiliary machinery essential to the propulsion and safety of the ship	15	22,5	5 *see* Note 2	7,5

NOTES
1. Athwartships and fore-and-aft inclinations may occur simultaneously.
2. Where the length of the ship exceeds 100 m, the fore-and-aft static angle of inclination may be taken as:

$\frac{500}{L}$ degrees

where L = length of ship, in meters.

- Part 5, Chapter 2 Oil Engines
  - Section 7 Control and monitoring of main, auxiliary and emergency diesel engines
  - Section 7.1 General
  - Section 7.5 Unattended machinery
  - Section 7.6 Oil engines for propulsion purposes
    - Table 2.7.1(a) Oil engine for propulsion purposes: Alarms and slow-downs (Partial table detail shown)

Item	Alarm	Note
Lubricating oil sump level	Low	Engines
Lubricating oil inlet pressure	1st stage low	Engines. Slow-down
Lubricating oil inlet temperature	High	Engines
Lubricating oil filters differential pressure	High	-

    - Table 2.7.1(b) Oil engine for propulsion purposes: Alarms and slow-downs (Partial table detail shown)

Item	Alarm	Note
Lubricating oil inlet pressure	2nd stage low	Automatic shut-down of engines, *see* 7.5.4

- Part 5, Chapter 12 Piping Design Requirements - Section 1 General
  - Section 1 General
  - Section 1.1 Application
  - Section 1.3 Design pressure
  - Section 1.4 Design temperature
  - Section 1.5 Classes of pipes
  - Section 1.6 Materials

- Part 5, Chapter 12 Piping Design Requirements – Section 2 Carbon and low alloy steels
  - Section 2.1 Carbon and low alloy steel pipes, valves and fittings
  - Section 2.2 Wrought steel pipes and bends
  - Section 2.3 Pipe joints – General
  - Section 2.4 Steel pipe flanges
  - Section 2.6 Welded-on flange, butt welded joints and fabricated branch pieces
  - Section 2.12 Other mechanical couplings

- Part 5, Chapter 12, Section 6 Valves
  - Section 6.1 Design requirements

- Part 5, Chapter 13 Ship Piping Design Requirements – Section 1 General requirements
  - Section 1.1 Application
  - Section 1.2 Prevention of progressive flooding in damage condition??
  - Section 1.3 Plans and particulars

- Part 5, Chapter 13 Ship Piping Design Requirements – Section 2 Construction and installation
  - Section 2.1 Materials
  - Section 2.2 Pipe wall thickness
  - Section 2.3 Valves - Installation and control

- Part 5, Chapter 13 Ship Piping Design Requirements – Section 3 Drainage of compartments, other than machinery spaces
  - Section 3.4 Tanks and cofferdams

- Part 5, Chapter 13 Piping Design Requirements - Section 12 Air, overflow and sounding pipes
  - Section 12.2 Materials
  - Section 12.4 Air pipes
  - Section 12.5 Termination of air pipes
  - Section 12.6 Gauze diaphragms
  - Section 12.7 Air pipe closing appliances
  - Section 12.8 Size of air pipes
  - Section 12.9 Overflow pipes
  - Section 12.11 Sounding arrangements
  - Section 12.12 Termination of sounding pipes
  - Section 12.13 Short sounding pipes
  - Section 12.16 Size of sounding pipes

- Part 5, Chapter 14 Machinery Piping Systems - Section 1 General requirements
  - Section 1.1 General

- Part 5, Chapter 14 Machinery Piping Systems - Section 2 Oil fuel- General requirements
  - Section 2.1 Flash point

- Part 5, Chapter 14 Machinery Piping Systems - Section 8 Lubricating oil systems
  - Section 8.2 Pumps
  - Section 8.3 Control of pumps
  - Section 8.4 Relief valves on pumps
  - Section 8.6 Maintenance of bearing lubrication
  - Section 8.7 Filters
  - Section 8.8 Filling arrangements
  - Section 8.10 Pipes conveying oil
  - Section 8.11 Lubricating oil drain tank
  - Section 8.12 Lubricating oil contamination

- Part 6, Chapter 2 Electrical Engineering - Section 1 General requirements
  - Section 1.1 General requirements
  - Section 1.2 Plans required for design review
  - Section 1.3 Plans required for supporting evidence
  - Section 1.7 Design and construction
  - Section 1.8 Quality of power supplies
  - Section 1.9 Ambient reference and operating conditions
  - Section 1.10 Inclination of ship
    - Table 2.1.1 Inclination of ship (Partial table detail shown)

Installations, components	Angle of inclination, degrees *see* Note 2			
	Athwartships		Fore-and-aft	
	static	dynamic	static	dynamic
Essential electrical equipment	15	22,5	5 *see* Note 3	7,5

NOTES
2. Athwartships and fore-and-aft inclinations may occur simultaneously.
3. Where the length of the ship exceeds 100 m, the fore-and-aft static angle of inclination may be taken as:
$\frac{500}{L}$ degrees
where L = length of ship, in meters, see Pt 3, Ch 1,6.1.

- Section 1.11 Location and construction
- Section 1.14 Alarms

- Part 6, Chapter 2 Electrical Engineering - Section 2 Main source of electrical power
  - Section 2.1 General requirements
  - Section 2.2 Plans required for design review
  - Section 2.3 Staring arrangements

- Part 6, Chapter 2 Electrical Engineering - Section 3 Emergency source of electrical power
  - Section 3.1 General
  - Section 3.2 Emergency source of electrical power in passenger ships

1.3 Received technical information and documentation

The required technical information and documentation received in respect of the lubricating oil tank and related systems have been appraised against the relevant sections of the Statutory instruments and Rule requirements referenced in section 1.2 above.

The received documents covered under LR design appraisal process for the lubricating oil tank and related systems are listed below for information.

As is common, during the design appraisal process, there have been several modifications to the design of the asset and its systems. Modifications have resulted through comments received from stakeholders, including OEMs and LR. Examples of such modifications are as follows

- Plan number MC / SCA – C. 6236, Lube Oil Service Tanks Main Engines - DCM 00107
  - Details presented on this plan show arrangement of the lubricating tanks for both engine types installed, including typical configuration for each engine foundation. Fincantieri had received comments from the engine builder over this plan which were only relating to height of the engine centreline and free space beneath the engine sump
  - Modifications as recommended by the engine builder are included within appropriate plans as presented in Table 1.3.1

- Plan number A5 D360 273, Rev 1, Lube Oil Service System Functional Diagram
  - List of modifications on the plan, detail three alteration descriptions DCM 0111, DCM 0107 and DCM 0196
    - Modifications had been made to the motor driven priming oil pump suction as well as engine mounted automatic filter. Additionally, modifications also made to sump tank venting / overflow, sounding system, cooler venting arrangement and engine breather arrangement

1.3.1 Hull structures plans

Plan No.	Rev.	Title	Approval document ref.
1A000200	0	Shell Expansion	TDS/HULL/I-34210, dated 28-Dec-2012
1A000230	2	Classification Drawing Zone 1	TTS/HULL/37798, 11-Apr-2014
1A000231	2	Classification Drawing Zone 2	MTES/HULL/16863847-3, 22-Apr-2014

Table 1.3.1 - Hull structural plans appraised

1.3.2 Machinery and piping plans

Plan No.	Rev.	Title	Approval document ref.
-	-	Project Guide L+V32/44 CR, Status 04.2010	ENS 27327-11, dated 02-Dec-2011
L32/44 CR	-	Application for Approval of an I.C. Engine	ENS 27327-11, dated 02-Dec-2011
C11.30000-105	A	LO Pump with Attachment L32/40	ENS 27327-11, dated 02-Dec-2011
DRW11440004780	A	LO System L32/44CR	ENS 27327-11, dated 02-Dec-2011
GSN110070	1	Piping Specification Booklet	TDS/ENG/SFS/34359, dated 11-Feb-2013
A5 D360 273	1	Lube Oil Service System Functional Diagram	TDS/ENG/35495, dated 30-Apr-2013
A5 D540 295	0	Fuel/Lube Oil Overflow and Air Vent System Functional Diagram	TDS/ENG/35833, dated 25-Jun-2013

Table 1.3.2 - Machinery and piping plans appraised

1.3.3 Electrotechnical plans

Plan No.	Rev.	Title	Approval document ref.
A6 N280 200	02	Power Plant and Distribution Electrical One Line Diagram	TTS/ETS/439493, dated 30-May-2014

Table 1.3.3 – Electrotechnical plans appraised

2. Incident information

On 23rd March 2019, Viking Sky was on a South-westerly passage to Bodø, along the West coast of Norway making way to Stavanger with an estimated arrival on 24th March. Weather conditions during the voyage were as forecasted but were expected to deteriorate during the afternoon and evening of 23rd March, so the master had agreement to continue onwards directly to Stavanger, following consultation with their shipping company[1]. Information provided to LR indicates the first incident occurred at 12:43:52 hrs UTC, and AIS data has been used to illustrate this as shown in Figures 2.1 and 2.2.

Figure 2.1 – Illustration of Viking Sky course on 23rd March 2019 (AIS Data)

Figure 2.2 – Illustration of Viking Sky course on 23rd March 2019 (Enlarged view)

Following the first incident a succession of events including further low lubricating pressure alarms and trips across all three of the operational diesel generators, as well as, including total loss of propulsion. Two blackout events also occurred within the first twenty-seven minutes of the incident.

The Flag authority, Norwegian Maritime Authority (NMA) issued a safety notice[2] based upon initial conclusions at the time of issuing of the notice, with the following recommendation: -

> "*Norwegian Maritime Authority recommends that all companies take necessary precautions to ensure the supply of lubricating oils to engine and other critical systems in expected weather conditions. This should be done in accordance with the engine supplier and, moreover, be included in the ship's risk assessments in the safety management system.*"

3. Norwegian Safety Investigation Authority

Following the incident, the Norwegian Safety Investigation Authority (formerly AIBN) initiated an investigation and had issued an interim report of the initial findings on 12th November 2019, along with a covering letter informing LR of the investigation in co-operation with United Kingdom's Marine Accident Investigation Branch (MAIB) and the United States Coast Guard (USCG).

It is understood that the initial phases of the investigation primarily focused on data gathering, factual information and preliminary analysis of the sequence of events of the accident category identified as 'Technical failure'[3].

The NSIA contacted Lloyd's Register Global Technology Centre on 4th March 2020, by email informing on the joint safety investigation into the Viking Sky incident. This was additionally followed up with a copy of a letter[4] dated 30th April 2020 received by email.

3.1 Computational fluid dynamic approach

NSIA had advised LR of their intention to conduct CFD calculations in their email dated 22nd January 2021, whereby NSIA informed LR about the status and next steps in the ongoing investigation.

NSIA outsourced the CFD analysis to SINTEF Ocean AS and the email outlined initial preliminary discussion with their chosen experts on necessary input for the analysis. NSIA requested LR's review of the proposal once their experts had completed this.

In the meantime, LR responded to the email received from NSIA on 22nd January 2021 with eight comments and observations with respect to the proposed approach for this analysis in our email dated 28th January 2021.

LR received the SINTEF proposal for the CFD analysis on 12th May 2021 (Memo - CFD simulation model and cases of Viking Sky Oil Sump N. 05 STBD[5]) which was reviewed by LR, and an additional twenty-eight comments were raised in our response dated 25th May 2021.

3.2 Sloshing analysis

LR received a copy of the SINTEF Ocean AS report[6] on 26th April 2022, this was followed up with an in-person meeting at MAIB office in Southampton, UK, 4th May 2022, where the report along with the investigation status was discussed.

Key take-aways from the meeting were as follows;

1. The investigation team indicated, at the current stage of investigation, there remained two areas of concern, whereby they believe LR may play an important role in improving safety at sea
    a. the Class approval process did not constitute an effective safety barrier in this specific case, and they intend to issue a safety recommendation requesting this safety issue to be adequately addressed
        i. LR reaffirmed in our email dated 25th May 2022 that the Rules have been satisfied, design of sump tank is compliant with governing requirements and sump tank design did not contribute to the incident
    b. this case illustrates the need for a UI (or similar tool) to enable designers, verifiers, class societies, RO's and Flag states to apply the SOLAS Regulation in a uniform manner. The investigation team stated the reality today is that each RO may apply their own interpretation which is only less transparent to the Flag in question and foresee a safety recommendation to LR to bring the safety issue to the attention of IACS and suggest a UI (or similar) is developed
        i. LR agreed that application of SOLAS Regulation 26.6 should be applied uniformly and with certainty
        ii. LR also believes the most effective means of achieving uniform implementation by all parties, including Flag States (not just 11 IACS members) is through an amendment to the existing SOLAS Regulation through a parallel safety recommendation to NMA to bring this issue to the attention of the IMO
2. The CFD simulations conducted by SINTEF are, as stated by the investigation team, not 100% accurate and have assumptions and limitations resulting in uncertainty, however, believe they are sufficiently realistic for the purpose and more realistic than any other representation or calculation they have seen

a. During the meeting LR suggested that they would also undertake their own CFD analysis of the arrangement as there was no feedback given to LR regarding the comments on the proposal SINTEF provided for the approach taken, concluding that the vast majority of the comments raised had not been addressed

b. NSIA provided their summary of the meeting in their email dated 11th May 2022 and had no objection for LR to undertake their own CFD simulations for this incident. This was welcomed by LR in their response dated 16th May 2022, as LR reiterated doubts and concerns discussed during the meeting

c. LR requested if SINTEF would be able to share the CFD model, provided to them by Fincantieri, with LR as a basis to pursue their own simulations. NSIA approached SINTEF regarding this, however, SINTEF had declined to share the model for reasons of IPR and protection of their propriety methods. LR was aware some form of modification or alterations had been made to the model as provided to SINTEF, however, LR requested a copy of the model from Fincantieri directly, which was received on 25th May 2022

4. LR Computational fluid dynamic report

LR approached their CFD analysis through application of different assessment conditions as follows;

- Static inclinations
- Regular motion analysis
- Dynamic irregular motion analysis
- Dynamic irregular motion analysis for incident

This approach was taken to cover aspects of work already conducted by interested third parties as well as exploration of conditions impacting performance of the subject lubricating oil tank.

Through this approach, LR has also considered elements that are not prescribed nor is there guidance available on parameters and methodologies of assessment against the governing statutory requirements.

Dynamic irregular motion analyses have utilised a rigid body, frequency-domain, linear seakeeping analysis to predict ship motion and hydrodynamic loads. IACS Recommendation No. 34 Standard Wave Data[7] has been used to determine fully developed wave spectrums for use with derived Response Amplitude Operators (RAO) and transfer functions to develop time traces. Parameters behind development of the data applied within these simulations have taken actual details, geometry, position (from AIS) and conditions of Viking Sky.

LR's 'CFD for oil sloshing'[8] (LR's CFD Report) is included in Appendix A.

4.1 Static inclinations

LR fully appreciates there are two distinct scenarios presented within the governing requirements as covered in sections 1.2.1 and 1.2.2, static and dynamic inclinations.

SOLAS requirement for static inclination only considers list (roll), as presented in Regulation 26.6, submission of technical information and documentation in respect of the approvals undertaken have already shown that the requirement is satisfied.

To this end, LR has also reconfirmed this requirement, by inclining the CFD model up to the maximum angle of 15°, for the worse condition of roll (to port) based upon the location and orientation of the subject lubricating oil tank. This is presented within LR's CFD Report as provided in the appendix to this report (Figure 5-2. 15° static roll; pump inlet fully submerged in oil).

Figure 4.1.1 - Illustration for static roll of 15°

Additionally, IACS have introduced a requirement for trim (pitch) as per UR M46 Ambient conditions - Inclinations[9], whereby a maximum static pitch angle of 5° was introduced. This maximum static pitch angle maybe reduced upon the length of ship (Note 4 of the UR) by the formula, $\frac{500}{L}$, if the length of the ship is greater than 100m. LR has also reconfirmed that this requirement is satisfied by inclining the CFD model to the maximum angle of 5°, for the worse condition of pitch (bow down 5°), whilst this is significantly greater that the maximum angle required by the UR. This is also presented within LR's CFD Report (Figure 5-3. 5° pitch; pump inlet fully submerged in oil).

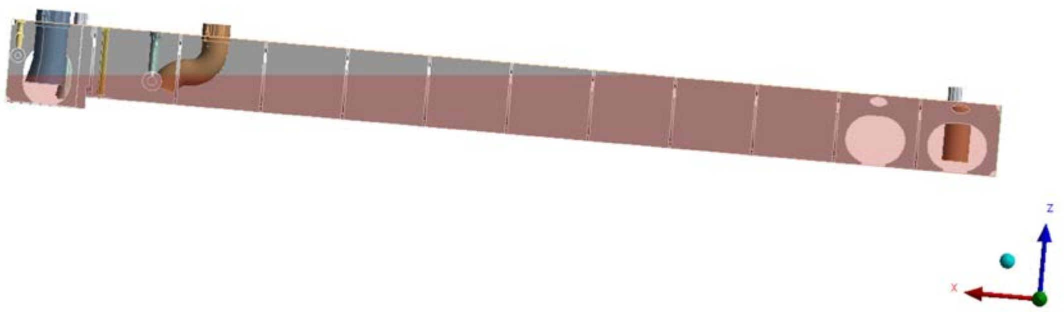

Figure 4.1.2 - Illustration for static pitch of 5°

During preliminary analysis conducted by NSIA they had suggested an assumption that, minimum filling should at least allow an angle of inclination of 22.5° roll and 7.5° pitch in a static condition, without suction of air. LR recognises that this was early within their investigation and subsequent understanding of the requirements have developed as the investigation progressed and subsequent outsourcing of CFD analysis to SINTEF came further into the investigation.

The assumption taken in the early stages of NSIA's investigation has demonstrated a subtle but important element of the current regulation and understanding the requirement for static and dynamic inclinations.

Nevertheless, LR had undertaken representation of the maximum dynamic inclinations, as required by the regulation, and applied these statically. Inclining the CFD model up to the maximum angle of 22.5°, for the worse condition of roll (to port) are presented within LR's CFD Report (Figure 5-1. 22.5° pitch; pump inlet fully submerged in oil).

Figure 1.1.3 - Illustration for static representation of dynamic roll of 22.5°

Inclining the CFD model to the maximum angle of 7.5°, for the worse condition of pitch (bow down 7.5°), is also presented within LR's CFD Report (Figure 5-4. 7.5° pitch; pump inlet not fully submerged in oil).

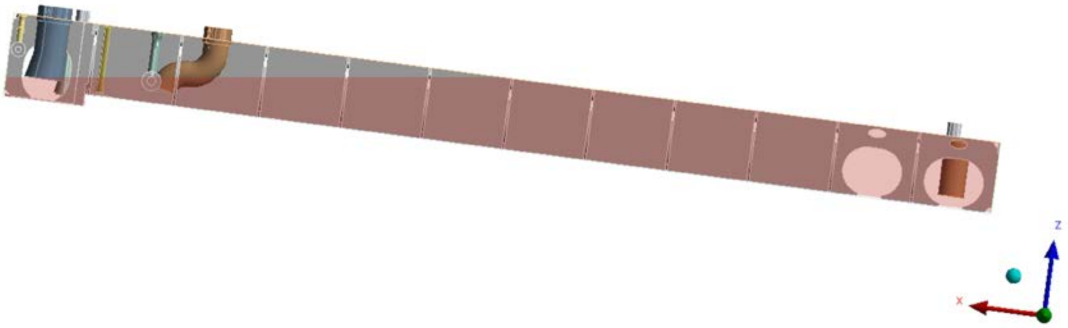

Figure 4.1.4 - Illustration for static representation of dynamic pitch of 7.5°

In this instance the lubricating inlet is not fully submerged as seen in the result, therefore implication is, non-compliance against the regulation.

It is to be noted, there is no specific reduction of maximum inclination angle as applied to static requirements or any UI or guidance on this. However, LR recognises dynamic inclinations are intended to represent assessment of this condition over a period, including any angle of and up to the maximum specified angles and not simply applied statically with a constant amplitude.

4.2 Regular motion analysis

During ongoing investigations being conducted by NSIA and exchange of comments with respect to the proposed approach for CFD analysis conducted, for and on behalf of NSIA, LR still had reservations about the approach taken and not had a response addressing these. NSIA had responded to our email, dated 16th May 2022, indicating they disagreed with our conclusion that several comments had not been addressed (NSIA email, SV: Viking Sky - CFD Report, dated 27th May 2022).

LR read, with interest, the regular motion analyses and assumptions presented within the report and how these could be considered representative for the governing requirements, to be able to confirm compliance, or otherwise, of the subject lubricating oil tank.

It is agreeable, currently, there is no published information, guidance, or interpretation of Regulation 26.6, as presented in section 2.1 of the SINTEF report.

LR recognises that our comments raised on variation of important factors had been given some consideration in the analysis, in particular differing motion period and phase.

To this end, LR decided to replicate the parameters presented for Case 10 of SINTEF report within their CFD analyses (Case 5 and Case 9, within LR CFD Report), recognising the simple motions being applied were considered as sinusoidal, constant amplitude motions, with a small simulation period, yet achieving maximum angles of inclinations as specified in the governing requirements, applied with the same motion period for both roll and pitch.

It is noted that representation of sinusoidal, constant amplitude motions does not reflect, nor statistically represent dynamic sea state conditions, with parameters used to describe these conditions being stochastic processes and continuous functions of time. Additionally, the approach taken does not appear to consider any effects of damping, as can be seen by the constant amplitude form applied. All systems are subject to some form of damping, with the simplest case being proportional to ship speed, and with damping applied, amplitude and period will decay over time.

Results obtained from these simulations are clearly presented within LR's CFD Report, Figure 5-6 through 5-8 (LR Case 5) and Figures 5-18 & 5-19 (LR Case 9), it is very clear from these two simulations undertaken and results obtained, phase difference will significantly alter performance of the model.

Based on this approach, one could confirm non-compliance, yet on the other hand, confirm compliance with the considered phase shift of simple constant amplitude motions applied.

4.3 Dynamic irregular motion analysis

Based on the outcomes of simple motions applied in section 4.2 LR took an opportunity to expand modelling of motions dynamically and based that approach on recognised industry practise comparable with hull structural longitudinal strength and fatigue analysis. It is well known and recognised the surface of the sea is irregular and random, being influenced by several factors.

Representation for this random process in a mathematical form has been studied since 1950's and is recognised this can be accurately characterised by superimposing many different regular waves of varying direction, height, length, and phase on each other.

Indeed, the IACS recommendation allows two approaches in the development of statistical representation for the sea surface, in which LR had applied the two parameter Pierson-Moskowitz[10] spectrum with assumption of deep sea and a fully developed sea state.

Modelling of wave data for the North Atlantic as presented in IACS Recommendation No. 34 was used to allow full 6 DoF, once in a twenty-year lifetime motions as well as understanding suppression of translations (heave, surge, and sway) as presented in section 3.3 and results obtained displayed in section 5.3, Figures 5-20 through 5-33, of LR's CFD Report. These scenarios simulated have also considered an equivalent linear roll damping coefficient, and hence damping for roll, recognising pitch (and heave) motions are predominantly in the frequency of encounter (rate with which the ship meets successive wave crests).

Choice of headings for simulation were based upon on the scenarios, as presented in Table 4.3.1, whereby the largest combination of rotational inclination angles for both pitch and roll were chosen.

In this instance the wave headings for 60 and 120 degrees, whereby, roll amplitudes are respectively 112% and 82.2% of the maximum inclination angles within the governing requirements. In a similar manner, chosen wave heading pitch amplitudes are respectively 86.7% and 145.3% of the maximum inclination angles of the requirements.

Relative heading	Roll		Pitch	
	Maximum Amplitude	Period	Maximum Amplitude	Period
60 deg	25.2°	15.7 seconds	6.5°	12.4 seconds
90 deg	25.2°	15.6 seconds	0.2°	7.0 seconds
120 deg	19.4°	15.2 seconds	10.9°	10.5 seconds
150 deg	8.3°	14.0 seconds	12.0°	11.7 seconds

Table 4.3.1 - Dynamic irregular motion analysis heading scenarios

For each of the irregular motions simulated, LR chose a simulation period of thirty minutes to assess performance of irregular seas on the lubricating system without changing course and maintaining speed. With this approach we are eliminating consideration over potential operating phenomena as presented in MSC.1/Circ. 1228[11] recognising the recommended actions to minimise effect of the phenomena.

It is observed, from the chosen wave headings results, a few events are seen where the VoF is shown to be lower than unity. However, it is also noted in comparison with each wave heading that the number of VoF events, lower than unity, are significantly reduced when translations are supressed.

Simulations for these cases were based on fully developed wave spectrums, resulting in a significant wave height of 14.5m and a period of 11.5 seconds. Putting this into context, information of Beaufort Wind Scale has been taken from the Royal Meteorological Society[12] for comparison against the scale as shown.

Wind Force	Description	Wind Speed	Specifications	Probable Wave Height		Sea State
				Min	Max	
8	Gale	39 - 46 mph	Twigs break off trees, generally impedes progress. Wave crests begin to break into spindrift	5.5	7.5	6 - 7
9	Strong Gale	47 - 54 mph	Slight structural damage (chimney pots and slates removed). Wave crests topple over, and spray affects visibility	7.0	10.0	7
10	Storm	55 - 63 mph	Seldom experienced inland; trees uprooted; considerable structural damage. Sea surface is largely white	9.0	12.5	8
11	Violent Storm	64 - 72 mph	Very rarely experienced, accompanied by widespread damage. Medium-sized ships lost to view behind waves. Sea covered in white foam, visibility seriously affected	11.5	16.0	8
12	Hurricane	73+ mph	Devastation. Air filled with foam and spray, very poor visibility	14+		9

Table 4.3.2 - Beaufort Wind Scale (partial table shown)

It is well known work undertaken by Walter Munk, during World War II, set the basis of significant wave height and this is determined by averaging height of the top one-third of all measured waves. This will of course, have instances of wave heights larger than the significant value. Therefore, one could position the motions applied as being a minimum sea state 8, violent storm, or higher, whereby continued heading, as applied with the simulations, would not be undertaken during normal operation for any extended period.

4.4 Dynamic irregular motion analysis for incident

LR has also simulated conditions at the time of the first incident experienced by Viking Sky on 23rd March 2019, 12:43:52hrs UTC[13]. Conditions modelled followed the same process as above to determine significant wave height and period to capture a statistically representative condition at time of incident.

This has included several sources in the determination of parameters, such as, sea elevation and influence of wind speed and direction. In addition, the JONSWAP[14, 15] spectrum as being considered more appropriate for limited fetch, wind driven seas representing local storm conditions at the actual coastal location of the event.

Motions generated were then modelled with different oil levels within the subject lubricating oil tank to compare performance. Results from these simulations are presented in section 5.4, Figures 5-34 through 5-44, in LR's CFD Report, with motions applied for this simulation as shown in Table 4.4.1 for ease of reference.

Relative heading	Roll		Pitch	
	Maximum Amplitude	Period	Maximum Amplitude	Period
210 deg	3.6°	13.9 seconds	5.9°	11.7 seconds

Table 4.4.1 Dynamic irregular motion analysis for incident

The three chosen oil levels for simulation were chosen to firstly, reflect the actual oil level within the subject lubricating oil tank, based upon manual sounding taken on the morning of the incident, secondly a conservative oil level, below minimum expected, and finally at the expected minimum filling level.

Simulations were conducted over a thirty-minute window and included simulations with and without translations, in a similar manner as the irregular motions applied as described earlier.

What is very apparent for the three cases simulated and figures presented in LR's CFD Report is oil levels play a significant role regarding performance, with and without translations applied. However, it is also evident that with the correct oil level in the subject lubricating tank there is no exposure of the inlet to air when considering the performance including translations applied.

5. Discussion

It is to be noted at the time the new construction project started, with design appraisal commencing in 2012, the requirement for Type Approval of engines was not a Rule requirement. The Rule requirement for TA was introduced in July 2016 following issuance of IACS UR M44[16] Rev.9. Nevertheless, the propulsion engines for the VIKING SKY had been Type Approved in December 2011. Although TA does not negate the appraisal of an engine as required by Part 5, Chapter 2, Section 1.1 of the Rules, part of the approval process requires submission of documentation verifying compliance with inclination limits as specified in Part 5, Chapter 1, Section 3.7, which follows IACS UR M46. For this case, these requirements were met through the submission of the MAN L+V32/44CR Project Guide and MAN's Application for Approval of an I.C. Engine, both approved by LR and both indicating that the inclination requirements of SOLAS Reg. II-1, 26.6 had been considered in the engine design.

In addition to the SOLAS Reg. II-1, 26.6 requirements, the VIKING SKY was also issued an EEDI Certificate (Certificate No. VEN 1491210), which includes consideration of the manoeuvrability of ships in "adverse conditions" as defined in MSC-MEPC.2/Circular 11[17], definition 1.1 with sea conditions and parameters as shown in Table 5.1.

Significant wave height h_s, m	Peak wave period T_p, s	Mean wind speed V_W, m/s
6.0	8.0 to 15.0	19.0

Table 5.1 - MSC-MEPC.2/Circular 11, definition 1.1

During the incident, there was a prolonged period to restore full propulsive power, due to numerous alarms and shutdowns / trips being experienced, compounded by lack of crew familiarity with the asset's systems. The alarms, automatic slow-down and engine shut-down requirements are defined in the Rules Part 5, Chapter 2, Section 7. The plans for these systems had been submitted and approved. After review of the Viking Sky Site Team investigation report[13] it does appear that the alarms and shutdowns were operating as intended with no issues identified.

NSIA has commented on the approach taken by LR for their CFD simulations stating the thirty-minute real time simulation is considered insufficient and may not be long enough to establish repeatability of motions. As discussed earlier, irregular motion analyses conducted, are by nature, stochastic processes and continuous functions of time. Due to the random and extreme conditions applied, once in a twenty-year life motion, in LRs simulations, the probability of any repeatability is considered negligible.

These computations have 'pushed the boundaries' by exploring conditions in excess of those expected to be encountered during normal sea-going service conditions, as well as exploring performance of the subject lubricating oil tank under conditions of the incident. Each of LRs thirty-minute real time simulations, with adaptive mesh refinement and time steps took thirty-six hours to conclude for each case.

LR is fully aware that with any analyses and simulations there are always limitations to consider, however for this investigation, we are of the opinion that work undertaken far exceeds what is expected for normal Statutory and Classification activities for the subject lubricating oil tank.

Recognising limitations under extreme conditions, asset responses cannot be considered as linear in nature, but in fact these are non-linear. This is due to several aspects, such as,

- variation in the underwater form as the asset moves through, and responds to, the waves
- increase in severity when decks become immersed, or bow leaves the water completely (recalling significant wave height for irregular motions of 14.5m)
- cross coupling of motions will occur
- heave and roll will induce pitching due to the hull form and therefore forces acting upon the hull will differ forward and aft
- the hull structure is not rigid

IACS UR M46 (originally published in 1982) is consistent with, and supports the application of SOLAS II-1, 26.6. Both IACS UR M46 and SOLAS II-1, 26.6 present the static and dynamic inclinations to be satisfied however, neither IACS UR M46 nor SOLAS II-1, 26.6 fully describe input parameters or criteria by which satisfactory operation under dynamic inclinations may be verified.

Prior to the incident of the VIKING SKY, LR had instigated a revision of the UR with a view to further defining the information required to be submitted to demonstrate compliance with the requirements of the UR. This work remains ongoing with the IACS Machinery Panel. Until the revision of IACS UR M46 has been finalised, agreed, and incorporated in to LR's procedures, LR took the initiative to introduce a Plan Approval Circular 2020/05 "Design Appraisal of main and essential auxiliary machinery for operation under conditions of static and dynamic inclinations" as a reminder to design appraisal specialists to ensure that static and dynamic inclinations are addressed during the approval stage.

Finally, at the beginning of this investigation, LR undertook a review of its fleet (current and historical) which had experienced incidents because of heavy weather. Of these incidents, spanning a period of over 50 years of records, we were unable to identify any failures / engine shutdowns which were attributable to the sump tank design or poor maintenance of the oil level in the sump tanks. Similarly, we received confirmation from the NMA that they have never issued, nor been requested to issue an exemption certificate to any asset under their flag from meeting the requirements of SOLAS Reg. II-1, 26.6.

6. Conclusion

LR confirms that its Rules and Regulations, in particular Part 5, Chapter 1, Section 3.7 (based on IACS UR M46 Ambient Conditions - Inclinations) were considered satisfied at the time of construction and consequently, LR considers the main propulsion arrangements as fitted on VIKING SKY are capable of satisfactory operation in service under the inclinations stated in SOLAS Reg. II-1, 26.6.

LR has undertaken extensive detailed modelling of the performance of the sump tank when subjected to the dynamic inclinations to support this investigation. Based on the results of the modelling, however, it has not been possible to conclude that the performance of the sump tank when subjected to the dynamic inclinations is unsatisfactory since the modelling can show satisfactory performance under the defined inclinations in SOLAS Reg. II-1, 26.6 or equally, unsatisfactory performance depending entirely upon the choice of those input parameters, due to lack of prescription in the Regulation, which are required to fully describe the dynamic inclinations such as, significant wave height, pitch period, roll period and, when considered simultaneously, phase shift between maximum pitch and maximum roll inclinations.

Initial findings in the NSIA interim report and all stakeholders acknowledge that the root cause of this incident was the failure to maintain the engine manufacturer's minimum recommended oil level in the sump tanks. It is noted that Wilhelmsen Ship Management AS have already taken steps and implemented changes to address this through updating of their ISM procedures and awareness training of their staff.

Recognising that any assessment of sump tank performance under the dynamic inclinations stated, but not fully defined, in SOLAS Reg. II-1, 26.6 produces contrasting results depending upon the choice of input parameters, LR has also undertaken further detailed modelling of the performance of the design when subjected to irregular motion based on wave data as described in IACS Rec. No.34 using a twenty-year wave return period.

Finally, this investigation has presented ambiguities in the defined requirements of SOLAS Reg.II-1, 26.6 and therefore LR recommends that cooperation is essential between all stake holders and flag administrations to address this at the IMO to provide clarity and allow a harmonised application of the requirement across the maritime industry.

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[5] Memo - CFD simulation model and cases of Viking Sky Oil Sump N. 05 STBD, Project No./File Code 302006011, Date 2021-05-11)

[6] Viking Sky - CFD Report, Sloshing analysis of Viking Sky Oil Sump N. 05 STBD, Report No. 1, Project No. 2105-0023, Revision 1.3, dated 07 March 2023

[7] IACS Recommendation No. 34 Standard Wave Data, Rev. 1 June 2000, Corr. November 2001

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[9] IACS UR M46 Ambient conditions - Inclinations, Rev. 1 June 2002

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[12] The Beaufort Wind Scale, Royal Meteorological Society website

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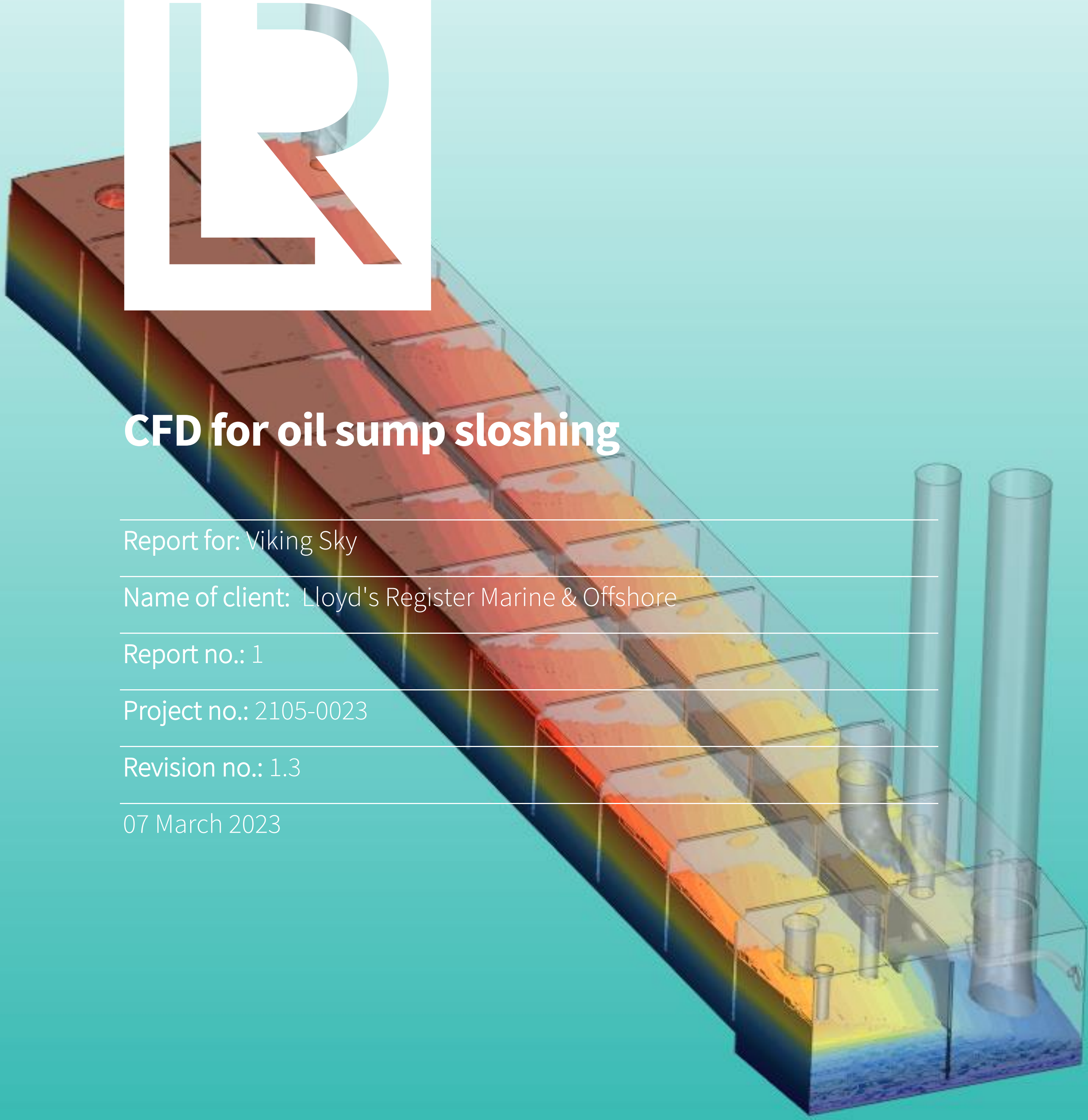
Appendix A CFD for oil sump sloshing



CFD for oil sump sloshing

Report for: Viking Sky

Name of client: Lloyd's Register Marine & Offshore

Report no.: 1

Project no.: 2105-0023

Revision no.: 1.3

07 March 2023

Summary

CFD for oil sump sloshing

Security classification of this Report: Distribute only after client's acceptance

Report no.:	Revision no.:	Report date:
1	1.3	07 March 2023

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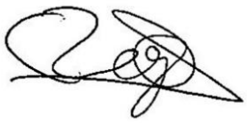

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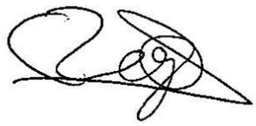

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Document control

Revision history

Revision No.	Date	Revision
0.10	03/02/2023	Draft report
1.0	07/02/2023	Final report
1.1	16/02/2023	Minor corrections
1.2	28/02/2023	Additional incident motion condition studied
1.3	07/03/2023	Typographic corrections

List of abbreviations

Abbreviation	Description
LR	Lloyd’s Register
SP	Ship Performance Group
TID	Technical Investigations Department
CFD	Computational Fluid Dynamics
kn	knots
DoF	Degrees of Freedom
SOLAS	Safety of Life at Sea
RAO	Response Amplitude Operators
IACS	International Association of Classification Societies
CG	Centre of Gravity
AP	Aft Perpendicular
AIS	Automatic Identification System
VoF	Volume of Fluid
HRIC	High-Resolution Interface Capturing
AMR	Adaptive Mesh Refinement
CFL	Courant-Friedrichs-Lewy

Executive summary[1]

At the request of Lloyd's Register Marine & Offshore (LR, the client), Technical Investigations Department (TID), performed Computational Fluid Dynamics (CFD) simulations to investigate the sloshing of the oil in oil sump No 5 of the Viking Sky IMO 9650420. The oil height relative to the pump inlet and oil cover of the pump inlet opening were the quantities of interest.

A range of scenarios was investigated including regular and irregular motions. The regular motions were combinations of roll and pitch (two degrees of freedom, 2DoF) modelled as sinusoidal motions. The irregular motions included translations and rotations in all axes (six degrees of freedom, 6DoF). Selected cases with different volumes of oil inside the sump were also simulated. Some of the irregular motion cases were also investigated under the effect of the rotations only (the translations were deactivated). The motions of the vessel at the location and time of the incident were also simulated. A total of 18 conditions were simulated including static rotations, regular (sinusoidal) motions and irregular motions. The motions at the time and location of the incident were also simulated. Instances when the oil sump pump inlet was exposed to air were identified for each simulated scenario.

Contents

1. Introduction

At the request of Lloyd's Register Marine & Offshore (LR, the client), Technical Investigations Department (TID), performed Computational Fluid Dynamics (CFD) simulations to investigate the sloshing of the oil in oil sump No 5 of the Viking Sky IMO 9650420. The oil height relative to the pump inlet and oil cover of the pump inlet opening were the quantities of interest.

A range of scenarios was investigated including regular and irregular motions. The regular motions were combinations of roll and pitch (two degrees of freedom, 2DoF) modelled as sinusoidal motions. The irregular motions included translations and rotations in all axes (six degrees of freedom, 6DoF). Selected cases with different volumes of oil inside the sump were also simulated. Some of the irregular motion cases were also investigated under the effect of the rotations only (the translations were deactivated). The motions of the vessel at the location and time of the incident were also simulated. In total, 18 conditions were analysed and are presented in this report.

2. Scope

The objective of this work was to monitor the oil height at the location of the oil sump's suction pump inlet under regular and irregular motions with a pre-defined volume of oil in the oil tank and identify instances where the oil sump pump inlet is not fully immersed in oil.

3. Ship Motions and Conditions for Investigation

3.1 Static Rotations

Static roll and pitch conditions were investigated separately using the angles specified in Safety of Life at Sea (SOLAS)[1].The five degrees pitch was added as an addition case. The oil filling level of the tank was 0.55m, corresponding to 5.42m^3 or 4766kg. Four conditions were investigated and are shown in Table 3-1.

Case	Roll (to port) Angle [deg]	Pitch (by stern) Angle [deg]
Case 1[2]	22.5	0
Case 2	15	0
Case 3	0	5
Case 4[2]	0	7.5

Table 3-1. Static rotation conditions

3.2 Regular Motions

The regular motions were chosen to match some of the scenarios investigated by Sintef[2]. The motions were described by simple sinusoidal functions for roll and pitch. These are summarised in Table 3-2. The oil level in the sump was 0.55m, corresponding to 5.42m^3 or 4766kg. The 7 second and 13 second pitch periods were identified by Sintef as the pitch peak response periods.

Case	Roll Angle [deg]	Roll Period [s]	Pitch Angle [deg]	Pitch Period [s]	Roll Phase Angle [deg]	Pitch Phase Angle [deg]	Comment
Case 5	22.5	17.5	-7.5	17.5	45	0	For comparison with Sintef's Case 10
Case 6	22.5	17.5	-7.5	7	0	0	First pitch peak period
Case 7	22.5	17.5	-7.5	13	0	0	Second pitch peak period. This period will result in the highest pitch response angles
Case 8	10	13	-2	9	0	0	Roll and pitch to match actual case at engine failure. Trim 0.5° bow down
Case 9	22.5	17.5	7.5	17.5	45	180	Same as Case 5 but with opposite pitch angle

Table 3-2. Regular motions investigated

[2] Maximum dynamic inclination represented statically

3.3 Irregular Motions

For the irregular motions, the motion response amplitude operators (RAOs) for all 6 DoF were obtained using potential flow calculations. The model used was that of the actual Viking Sky. Using the RAOs, the motion time were calculated for the given significant wave height, zero up-crossing period and wave spectrum. The irregular motion cases were based on once-in-a-20-year-lifetime encounter. The wave scatter diagram used is the International Association of Classification Societies (IACS) Rec.34 North Atlantic wave scatter diagram[3]. Ship structural designs are normally based on a design life (25 years in this case) multiplied with a routing factor of 0.85. This results in a wave scatter diagram equal to 21 years. As the calculations are based on long crested seas, which is a conservative assumption, the 20-year envelope values are used for the analysis[4]. The Pierson-Moscowitz wave spectrum was used with a speed of 6.5kn. The conditions are shown in Table 3-3 where Tz is the zero-up-crossing period in seconds and Hs is the significant wave height in metres. The highlighted values were chosen for investigation as these are most likely to result in the pump inlet becoming exposed to air.

Tz (s)	4.50	5.50	6.50	7.50	8.50	9.50	10.50	11.50	12.50	13.50	14.50	15.50	16.50
Hs (m)	2.59	5.20	7.88	10.21	12.03	13.33	14.16	14.55	14.56	14.18	13.39	12.05	9.47

Table 3-3. 20-year IACS Rec.34 envelope curve

The motions of the vessel's centre of gravity (CG) were derived for headings between 60° and 150° in increments of 30°. For clarity, the definition of the ship motions and headings is shown in Figure 3-1. The location of the ship's CG was defined with the reference to the ship's aft perpendicular (AP) and the baseline. Its location is shown in Table 3-4 and it was taken from the reference simulation that was given to TID by Fincantieri. LR's in-house software was used to generate the motions for 1800s of real time with a timestep of 0.2s. This resulted in twelve possible scenarios for CFD investigation. To narrow the investigation down, the conditions investigated were those where high values for roll and pitch occurred in the time history of the motions. The investigated conditions are summarised in Table 3-5.

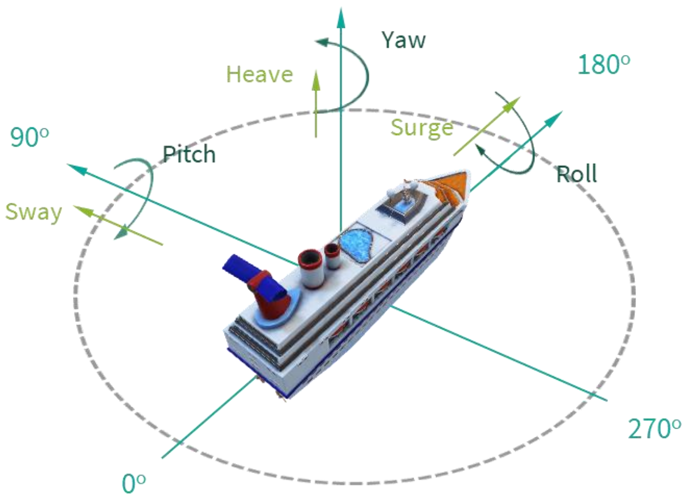

Figure 3-1. Definition of ship motions and headings

X	Y	Z
90.88	0.0	13.59

Table 3-4. Viking Sky's location of CG

Case	Wave Heading [deg]	Significant Wave Height [m]	Wave Period [s]	Oil Level [m]	Oil Volume [m^3]	Comment
Case 10	60	14.5	11.5	0.55	5.42	High pitch and high roll, rotations and translations
Case 11	60	14.5	11.5	0.55	5.42	As Case 10 without translations
Case 12	120	14.5	11.5	0.55	5.42	High pitch and high roll, rotations and translations
Case 13	120	14.5	11.5	0.55	5.42	As Case 12 without translations

Table 3-5. Irregular motions investigated

3.4 Incident Motions

Simulations were also performed using motion data derived from the weather and sea conditions at the location and time of the incident. Automatic Identification System (AIS) data was used to capture the ship's location, heading and speed at the time of the first recorded incident. Data from multiple sources such as the Copernicus Sentinel-3A's Synthetic Aperture Radar Altimeter, WAVEWATCH III and National Oceanic and Atmospheric Administration's, National Data Buoy Centre was used to define sea state and capture the significant wave height, period and direction. The waves were not fully developed as they were driven by local storm conditions, therefore the ship response motions are based on the JONSWAP wave spectrum with a gamma factor equal to 3.3.

The heading at the incident was determined at 210 degrees and is summarised in Table 3-6. Different oil filling levels were simulated as presented.

Case	Heading [deg]	Significant Wave Height [m]	Wave Period [s]	Oil Filling Level [m]	Oil Volume [m^3]	Comment
Case 14	210	7.2	10.8	0.32	2.70	Incident condition, rotations and translations
Case 15	210	7.2	10.8	0.32	2.70	As Case 14 without translations
Case 16	210	7.2	10.8	0.476	4.55	As Case 14 with a conservative oil height
Case 17	210	7.2	10.8	0.476	4.55	As Case 16 without translations
Case 18	210	7.2	10.8	0.5145	5.04	As Case 14 with required minimum oil height

Table 3-6. Incident motions

4. CFD Methodology

StarCCM+ v17.04.007 was used for the CFD simulations. The main particulars of the setup are presented in this section.

4.1 Geometry

The geometry of the oil sump included internal baffles and piping and was provided to TID from Fincantieri. The piping included the suction pump pipe, the oil return pipe and the air vents. An atmospheric boundary condition was used for the outlet boundaries at the top of the suction pipe and air vents. To minimise the risk of oil escaping out of the atmospheric boundaries during severe sloshing events the length of the pipes was increased. The oil sump geometry that was used in the CFD is shown in Figure 4-1.

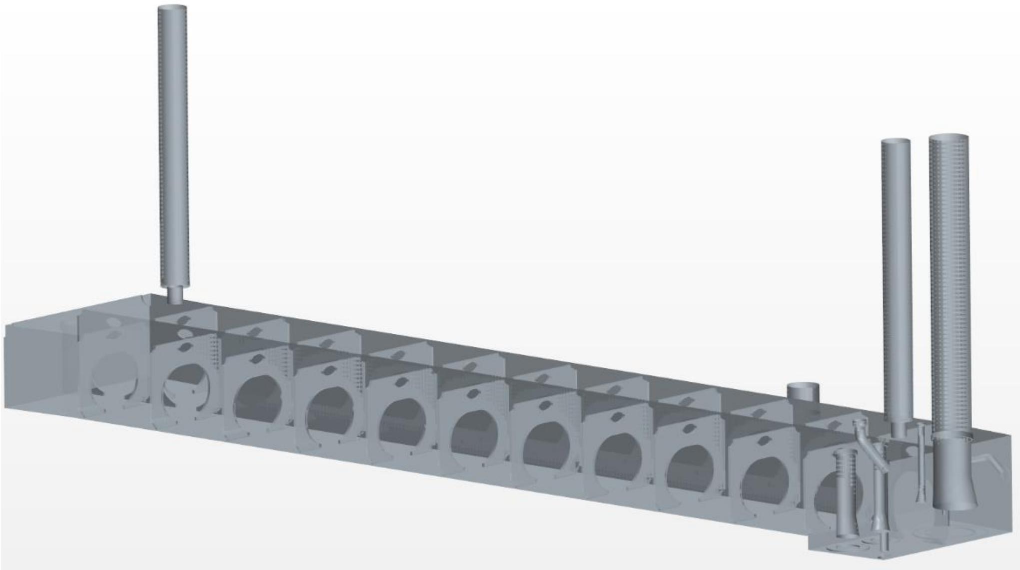

Figure 4-1. Viking Sky's oil sump No 5

4.2 Coordinate Systems

The motions were defined with respect to the ship's CG. For details of the motion set up the reader is referred to Appendix A.1. A coordinate system located at the suction pump inlet, shown in Figure 4-2, was created for monitoring purposes.

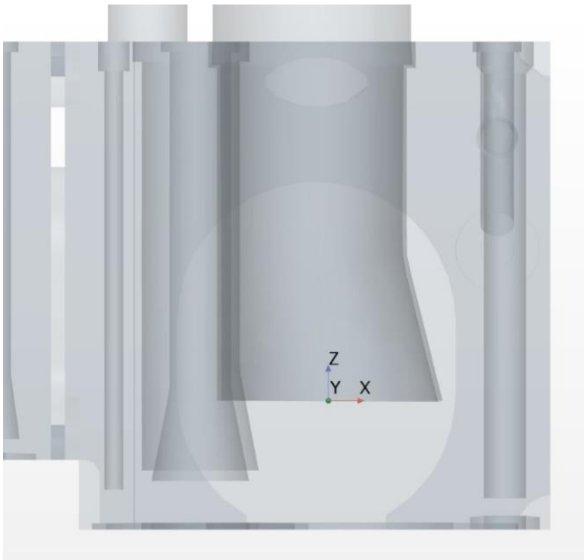

Figure 4-2. Coordinate system at suction pump inlet

4.3 Motion Implementation in StarCCM+

The motions of the oil sump were set up as translations with superposed rotations. The order of rotations was roll-pitch-yaw and each rotation managed the coordinate system of the child rotation. For a more detailed description, the reader is referred to Appendix A.2.

A table with the translation velocities and rotation angles as functions of time was imported in StarCCM+. An extract of the table for the irregular waves case 2 (Table 3-5) is shown in Figure 4-3. The first column is the time in seconds (s). The next 3 columns are the x (surge), y (sway) and z (heave) position of the CG in metres (m). For example, at time 0.2 seconds, it is -0.00019m from its initial position at time 0s while at time 1s, the CG is located -0.0005m from its position at time 0s. From these, the translation velocities are derived (V_Surge, V_Sway, V_Heave) using the equation for velocity (Equation 4-1). In turn, these values were used in the relevant field functions, interpolating the translation velocities from the table for each timestep.

$$\boldsymbol{v} = \frac{\boldsymbol{x_2} - \boldsymbol{x_1}}{\boldsymbol{t_2} - \boldsymbol{t_1}}$$

Equation 4-1. Velocity equation

Then the rotation angles for roll, pitch and yaw are given in the motions data table. In this case, the angles are in radians (rad), and they are repeated in the last three columns as Roll_rotation_angle, Pitch_rotation_angle and Yaw_rotation_angle, respectively. These are finally used in the appropriate field functions interpolating the data to derive the rotation angles for each timestep.

1	Time	Surge	Sway	Heave	Roll	Pitch	Yaw	V_Surge	V_Sway	V_Heave	Roll_rotation_angle	Pitch_rotation_angle	Yaw_rotation_angle
2	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0.2	-0.00019	-0.04631	0.018715	0.000265	0.000004	-3.7E-05	-0.00097	-0.23155	0.093573	0.000265	0.000004	-0.000037
4	0.4	-0.00035	-0.085161	0.045404	0.000218	0.000008	-6.8E-05	-0.00079	-0.19426	0.133446	0.000218	0.000008	-0.000068
5	0.6	-0.00046	-0.114917	0.079957	-0.00015	0.000012	-0.00009	-0.00055	-0.14878	0.172766	-0.000146	0.000012	-0.00009
6	0.8	-0.00051	-0.134213	0.121839	-0.00083	0.000015	-0.0001	-0.00025	-0.09649	0.209408	-0.000829	0.000015	-0.000102
7	1	-0.0005	-0.142015	0.170079	-0.00183	0.000016	-0.0001	0.000084	-0.03901	0.241199	-0.00183	0.000016	-0.000102

Figure 4-3. Example of motions table

4.4 Boundary Conditions

All of the walls are modelled as no-slip walls. The opening of the oil return pipe was closed and modelled as no slip wall. The suction pipe outlet was modelled as an atmospheric outlet where air was allowed to go both in and out of the domain, but backflow of oil was not allowed. The air vents outlets were setup in the same manner. The boundary conditions are shown in Figure 4-4.

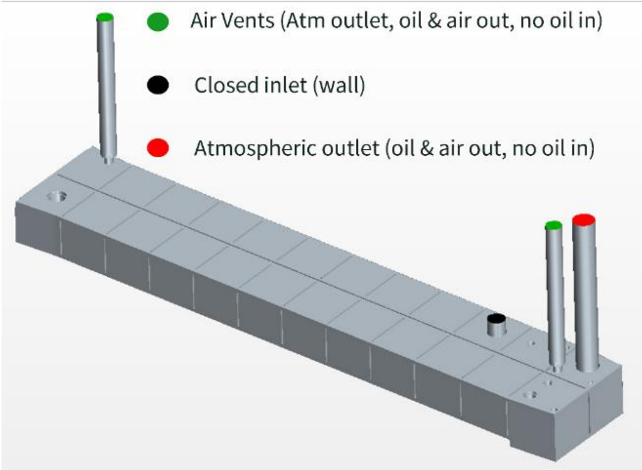

Figure 4-4. Boundary conditions

4.5 Physics Models

The flow was treated as three-dimensional, unsteady, incompressible, and turbulent with gravity included as it is required for sloshing applications. The realizable k-ε turbulence model was used to model turbulence. This is a robust and relatively inexpensive model which makes it a suitable model for such applications. The two-layer wall functions treatment was selected to account for the range of non-dimensional wall distance values (y+ or y-plus) expected to be encountered in the simulations. The segregated flow model was selected with 2^{nd}-order discretisation of the convection terms. The multiphase mixture was comprised of liquid oil and air. The properties of the fluids were constant and are shown in Table 4-1. The volume of fluid (VoF) method was used to solve the free surface between the two fluids with the high-resolution interface capturing (HRIC) method for the convection and 2^{nd}-order accurate discretisation.

Property	Oil	Air
Density (kg/m^3)	880.0	1.18415
Dynamic Viscosity (Pa-s)	0.02816	1.85508E-5

Table 4-1. Properties of oil and air

4.5.1 Baseline Mesh

A trimmed mesh was used as the initial baseline mesh. The target cell size for the surface and volume mesh was set to 3.1cm. The minimum cell size of the surface mesh was set to 4mm in order to capture the smaller geometrical features such as surfaces of small radius. Since wall functions were used, one layer of prism cells was created.

4.5.2 Adaptive Mesh Refinement

The adaptive mesh refinement (AMR) technique was used to refine the mesh around the moving free surface of the oil. AMR is well suited for sloshing applications as the shape and location of the free surface is not known a-priori. Therefore, without AMR the mesh would need to be appropriately fine everywhere in the solution domain. This would result in a very high total cell count, making the simulations prohibitively slow. For instance, in this sloshing example, the mesh would need to be on the order of 17 million cells, simulating approximately 2 minutes of flow time in about 48 hours. With the AMR, the solution is initialised on a coarse mesh and the model detects the free surface, refining only those cells that define the interface between the two phases. Using appropriate criteria, the AMR model tracks the interface and predicts its potential location at the next refinement iteration. Then it refines only those cells that contain the free surface and those cells where the free surface is expected to be. Cells that are either completely full of oil or air, are coarsened. Excessive refinement of the cells would also have an adverse impact on the simulation by creating the demand for unnecessarily low Courant-Friedrichs-Lewy (CFL) number, slowing the simulation down and possibly creating numerical instabilities if the CFL criterion was not fulfilled. To avoid that, the refinement was limited to two refinement levels (i.e., two successive refinements from the initial cell size) or to cells no smaller than approximately 0.008m. When coarsening the refined cells, the AMR did not coarsen the mesh further than the initial mesh. The AMR solver was set to trigger every five timesteps.

4.5.3 Adaptive Timestep

To speed up the simulations the adaptive timestep technique was also used. Using the free surface CFL condition as a criterion, this method adjusts the timestep targeting a specific CFL number on the free surface. In this case, time-accurate solutions were sought. As such, the maximum CFL limit was defined as 0.5 as per standard CFD practices for time-accurate simulations. To limit the number of requests for unnecessarily low timestep, the method applies two smoothing steps on the timestep condition and ignores up to 0.5% of the cells that request too low a timestep.

To avoid large changes in the timestep that could introduce instabilities, the timestep was allowed to increase only by a factor of two. The maximum timestep was on the order of 0.016s. There was no limit to how fast the timestep could decrease.

4.6 Monitors

The immersion of the pump inlet was monitored by tracking the oil free surface on the walls of the suction pipe. The suction pipe has a finite thickness and the oil is in contact with both the inner and outer surfaces. As such, the height readings which are relative to the inlet opening could be either of the inside or the outside wall. This is a conservative approach because when the minimum height is greater than zero, the fluid is in contact both with outside wall and the inner wall. When the minimum height reaches zero, it indicates that the fluid is not in contact with the inner wall anymore. However, this does not give an absolute measure of how much of the inlet is exposed to air.

To gain insight about the absolute level of oil relative to the pump inlet especially when the oil level has dropped below the inlet, an extra monitor was created. This monitor consisted of a point probe moving along the centreline of the suction pipe, like a floater on the free surface. This probe recoded the height of the oil relative to the inlet. These monitors and probes are presented in Figure 4-5 where the oil free surface inside the pipe is represented by the green line. The centreline is shown in red and the point probe created by the intersection of the centreline and the free surface is shown in black.

Finally, a monitor was created to calculate the percentage of the inlet area covered by oil. This is named surface average VoF and is used in presenting the results below (section 5). The section used for this, is shown in Figure 4-6. For further details the reader is referred to Appendix A.3.

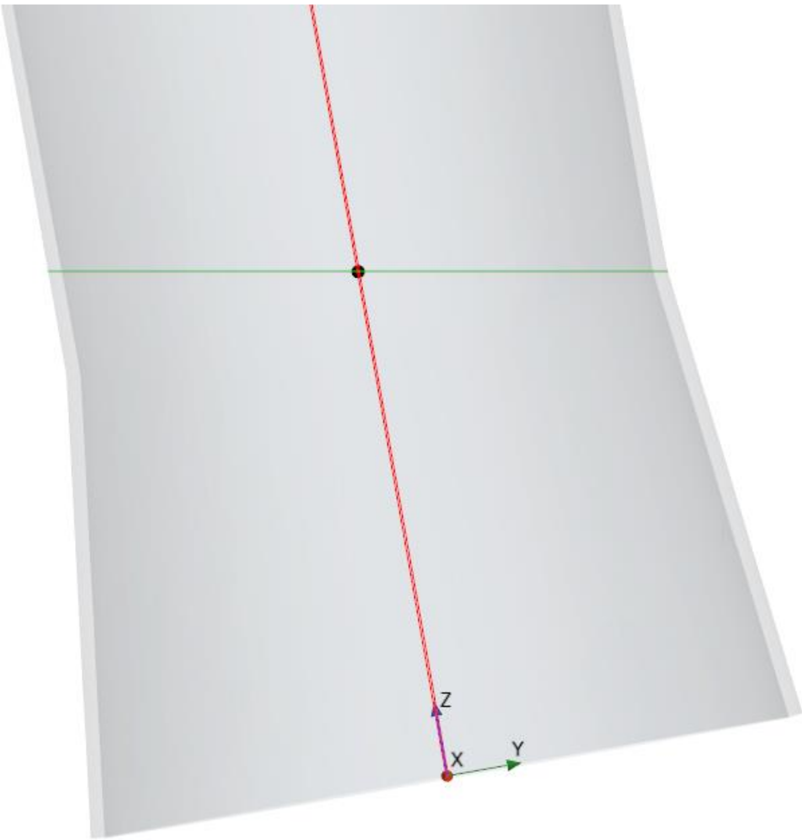

Figure 4-5. Free surface of oil (green), centreline (red), point probe (black) and pump inlet coordinate system (pipe centreline)

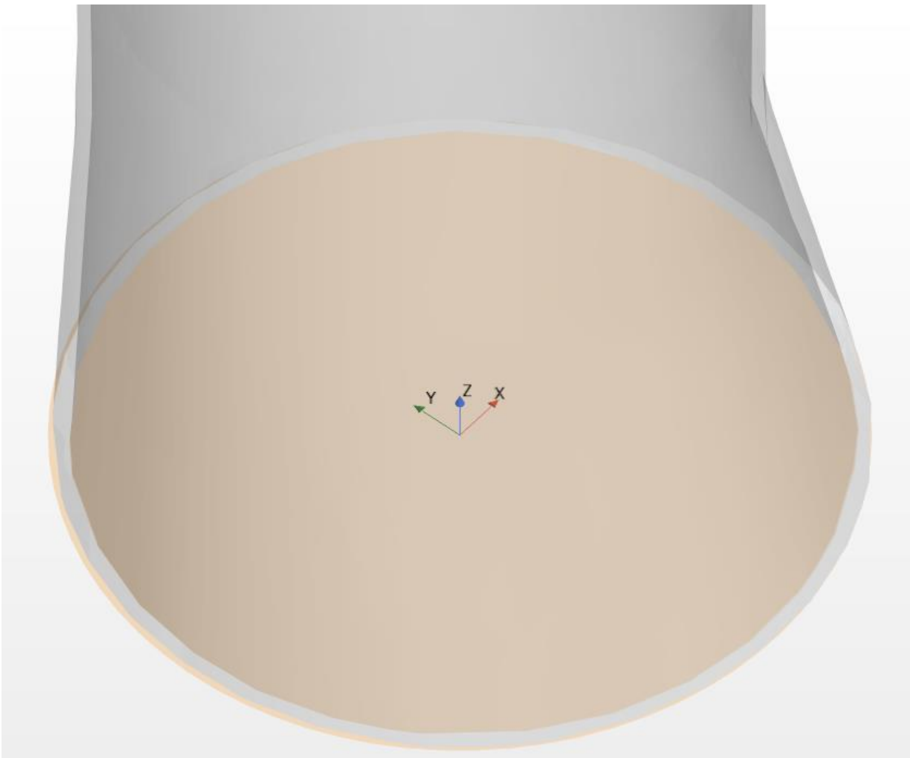

Figure 4-6. Section at pipe inlet for monitoring the surface average volume of fluid of oil

5. Results

5.1 Static Rotations

5.1.1 Case 1[3]

Figure 5-1 shows the free surface of the oil that at 22.5° static roll along with the plot of the surface average VoF at the pump inlet and the roll and pitch angles. From the tank model it is seen that the pump inlet is fully immersed. This is confirmed by the plot of the surface average VoF that is 1 showing that the pump inlet is not exposed to air.

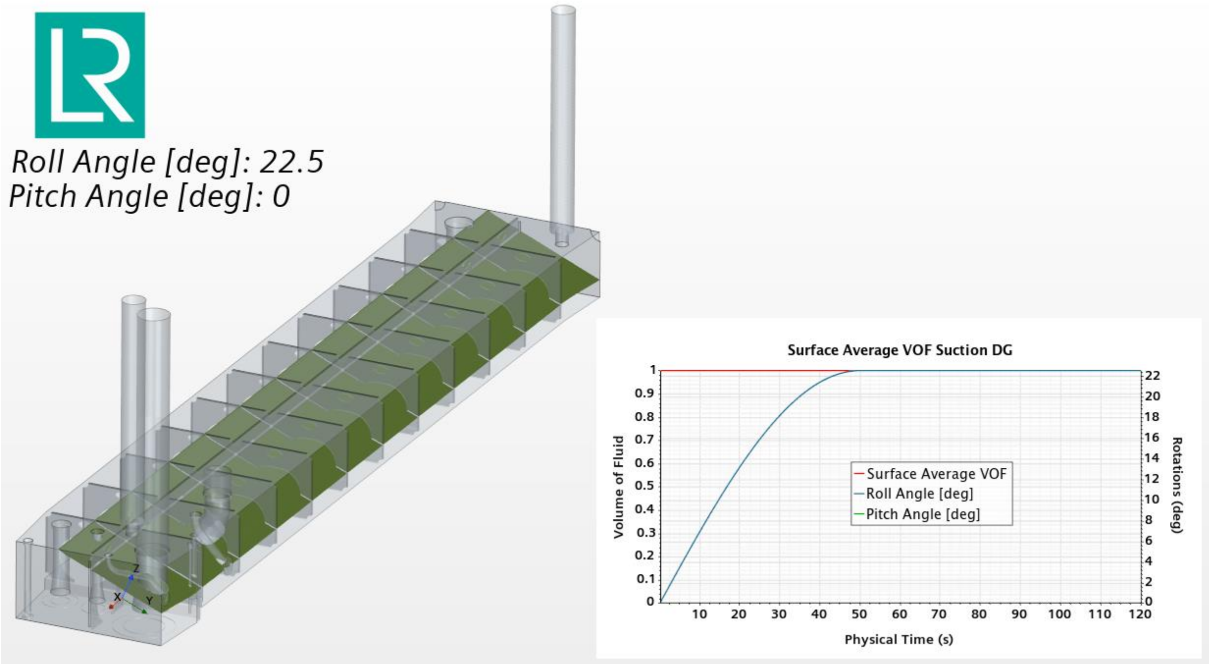

Figure 5-1. 22.5° static roll; pump inlet fully submerged in oil

5.1.2 Case 2

Figure 5-2 shows the free surface of the oil that at 15° static roll along with the plot of the surface average VoF at the pump inlet and the roll and pitch angles. It is seen that the pump inlet is fully immersed in the oil and the surface average VoF is 1.

[3] Static representation of a dynamic inclination

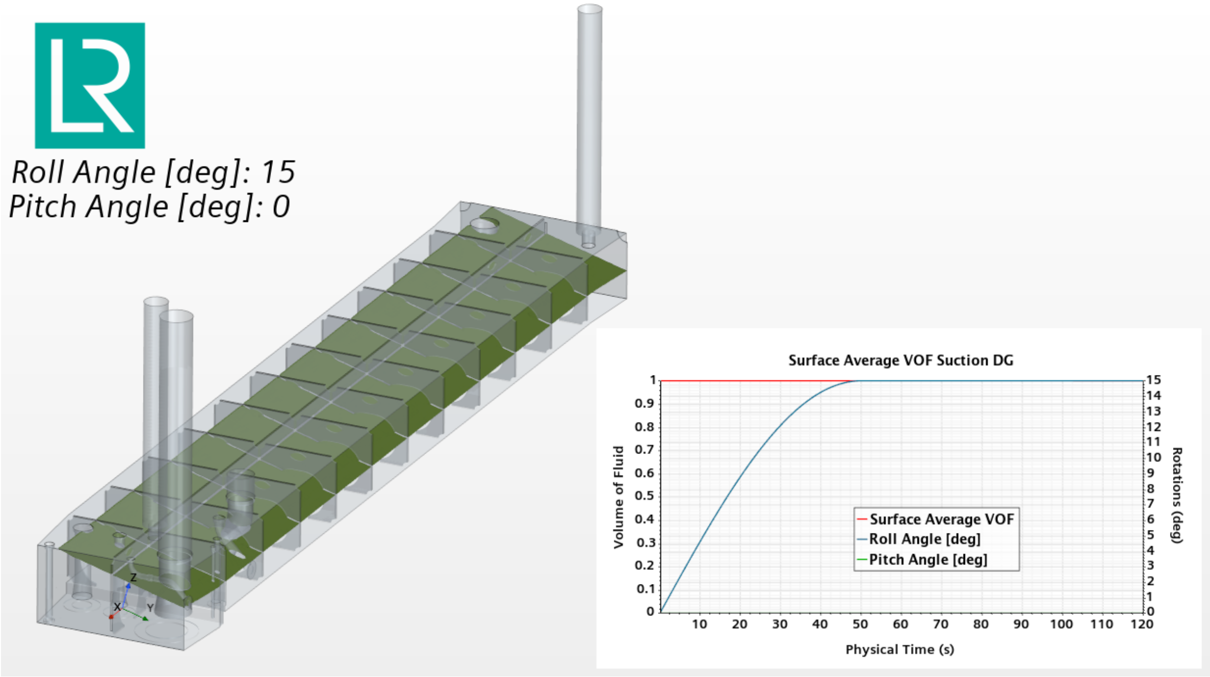

Figure 5-2. 15° static roll; pump inlet fully submerged in oil

5.1.3 Case 3

Figure 5-3 shows the free surface of the oil that at 5° pitch by stern along with the plot of the surface average VoF of oil at the pump inlet and the roll and pitch angles. It is seen that the pump inlet is fully immersed in the oil and the surface average VoF is 1.

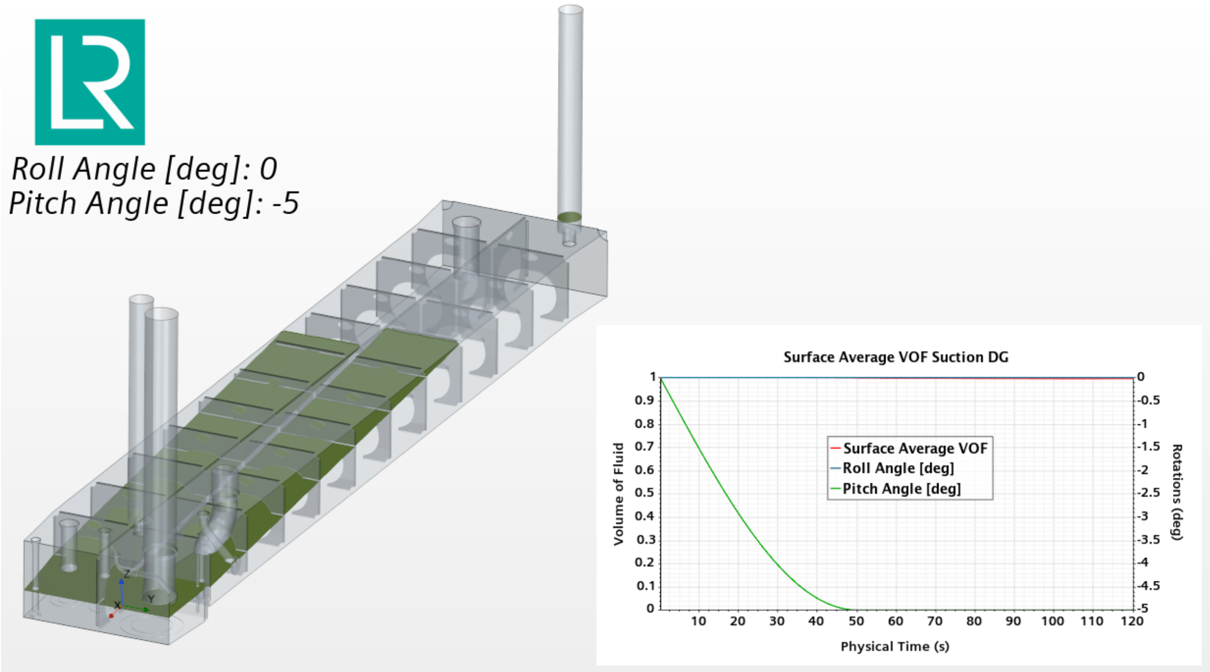

Figure 5-3. 5° pitch; pump inlet fully submerged in oil

5.1.4 Case 4[4]

Figure 5-4 shows the free surface of the oil that at 7.5° pitch by stern along with the plot of surface average VoF at the pump inlet and the roll and pitch angles. It is seen in Figure 5-5 that the pump inlet is not fully immersed and the surface average VoF at the inlet is approximately 77% suggesting the pump inlet is partially exposed to air.

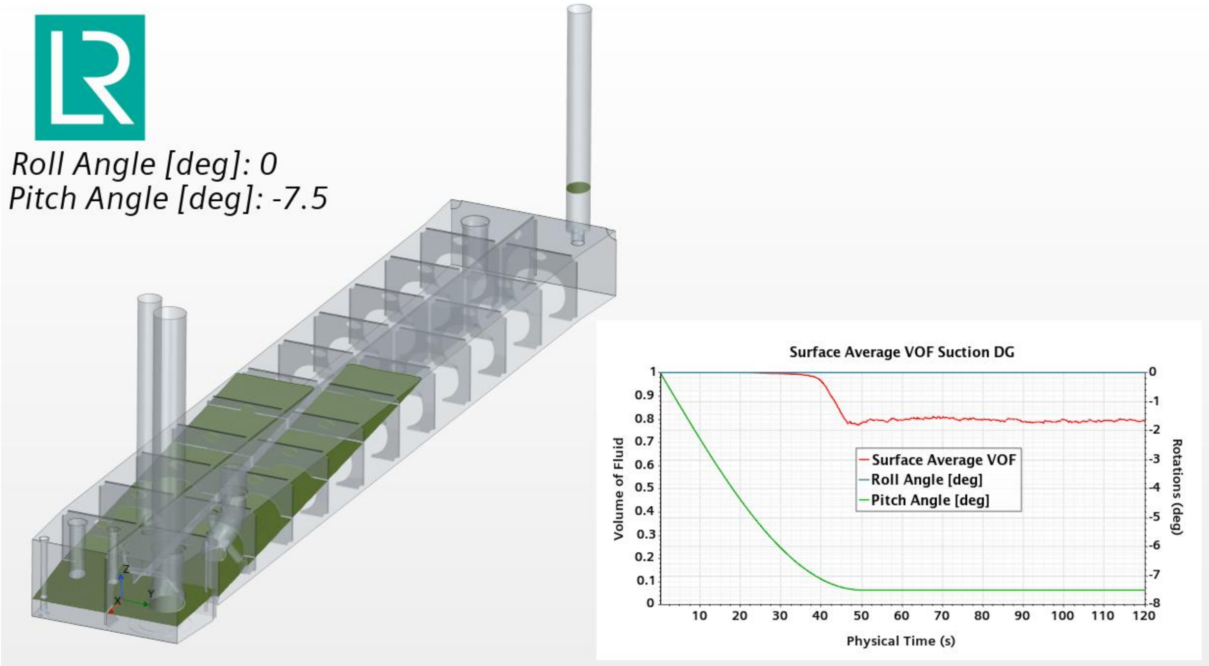

Figure 5-4. 7.5° pitch; pump inlet not fully immersed in oil

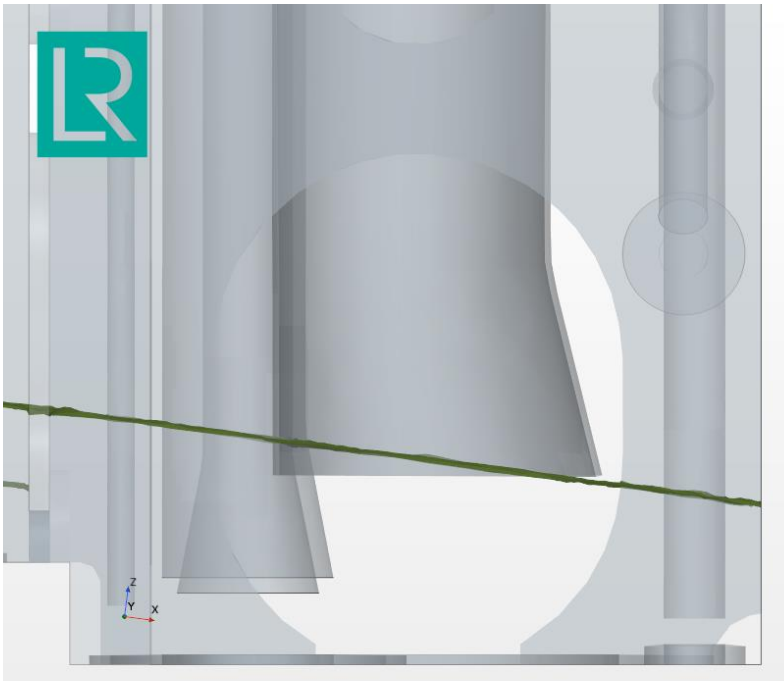

Figure 5-5. Pump inlet immersion; close view

[4] Static representation of a dynamic inclination

5.2 Regular Motions

5.2.1 Case 5

Figure 5-6 presents the surface average VoF of oil at the suction pipe inlet. It is observed that the surface average VoF drops to zero periodically, with a period similar to that of the regular motions (approximately 18s). Figure 5-7 presents the oil height on the pipe based on the free surface monitors described in paragraph 4.6. The oil height drops below the inlet level and as low as the tank bottom (0.183m below the pipe's inlet). Figure 5-8 presents an example of the oil's distribution in the tank at an instance when the suction pipe inlet is completely exposed to air. The contours show the height of the free surface, measured from the tank's bottom directly under the pipe.

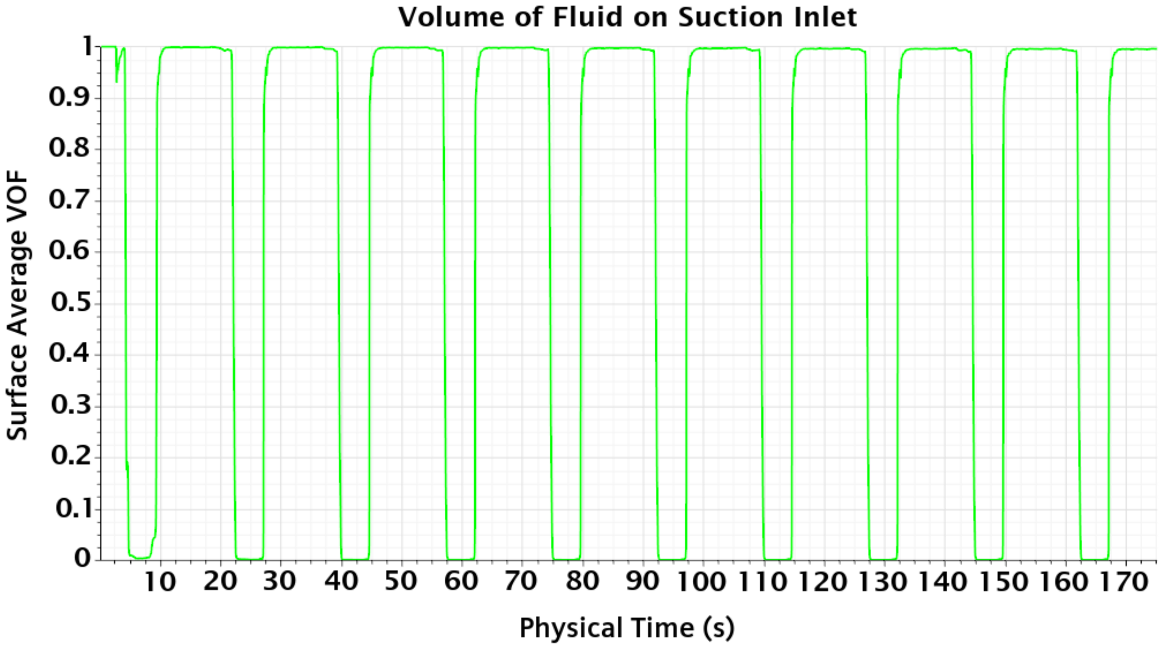

Figure 5-6. Case 5; surface average VoF of oil at suction inlet

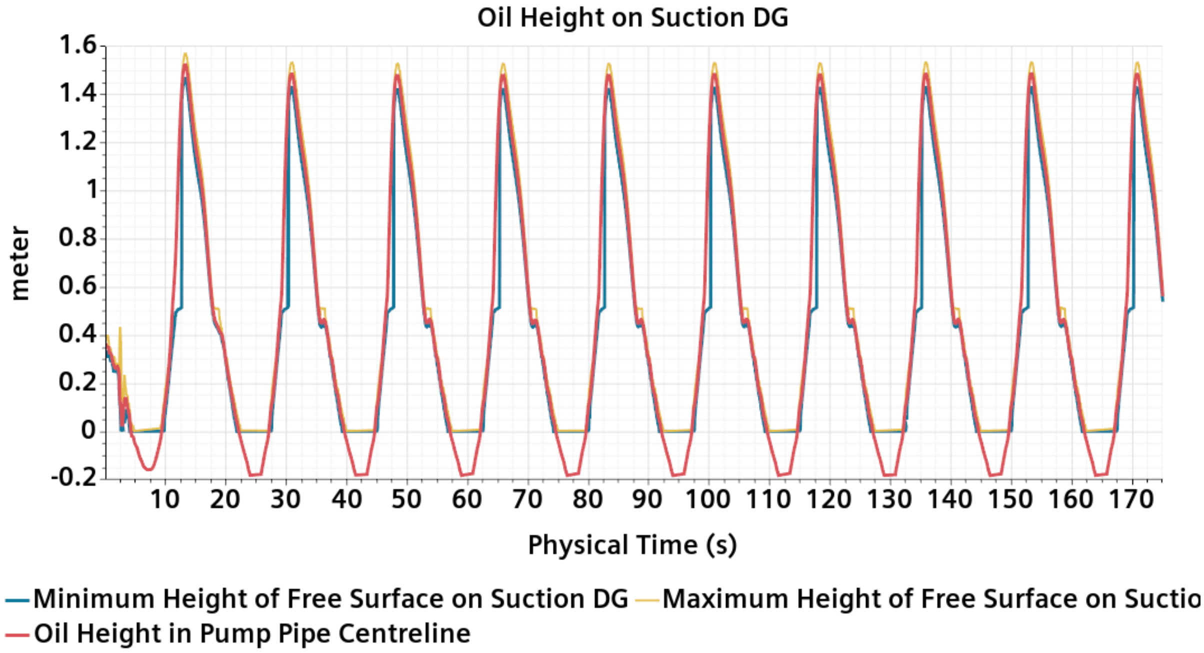

Figure 5-7. Case 5; oil height in suction pipe

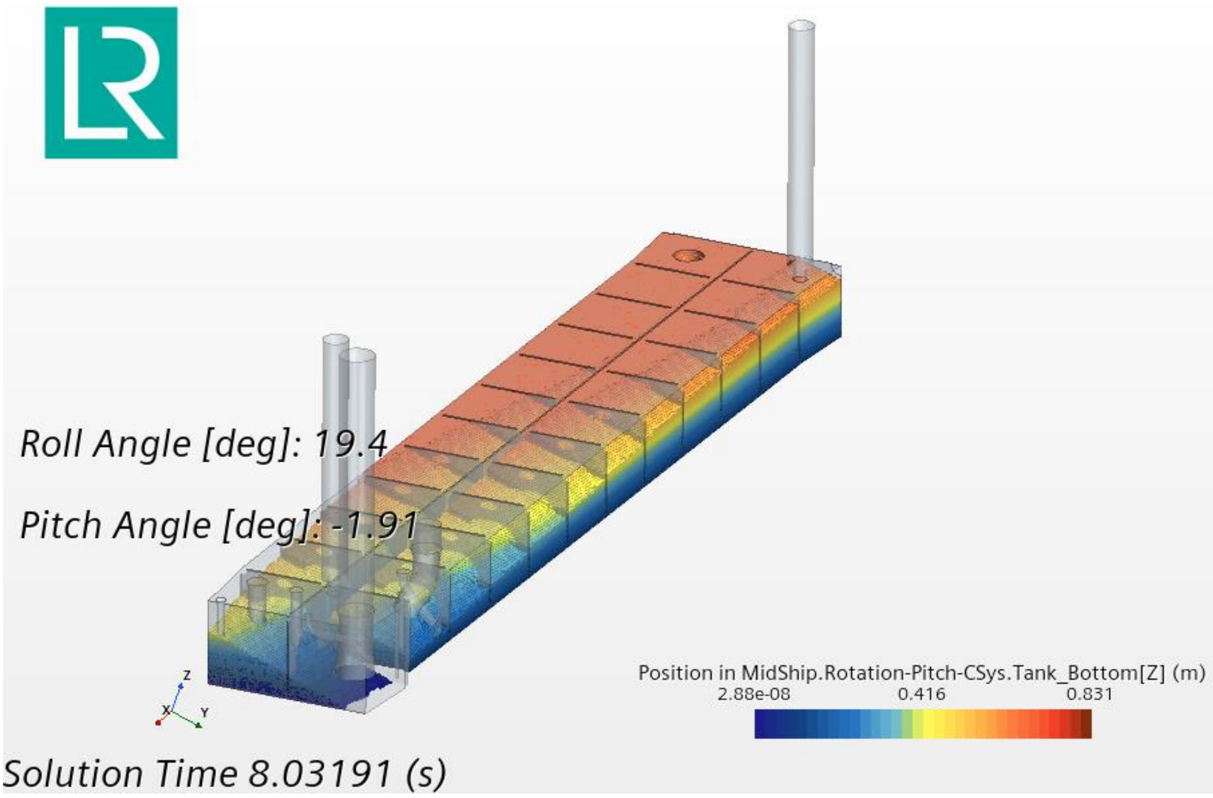

Figure 5-8. Case 5; oil height based on oil threshold

5.2.2 Case 6

Figure 5-9 presents the surface average VoF of oil at the suction pipe inlet. It is observed that the surface average VoF drops to zero periodically and the period that this happens alternates between approximately 16s and approximately 20s. Figure 5-10 presents the oil height in the pipe based on the free surface monitors. The oil height drops below the inlet level and as low as the tank bottom.

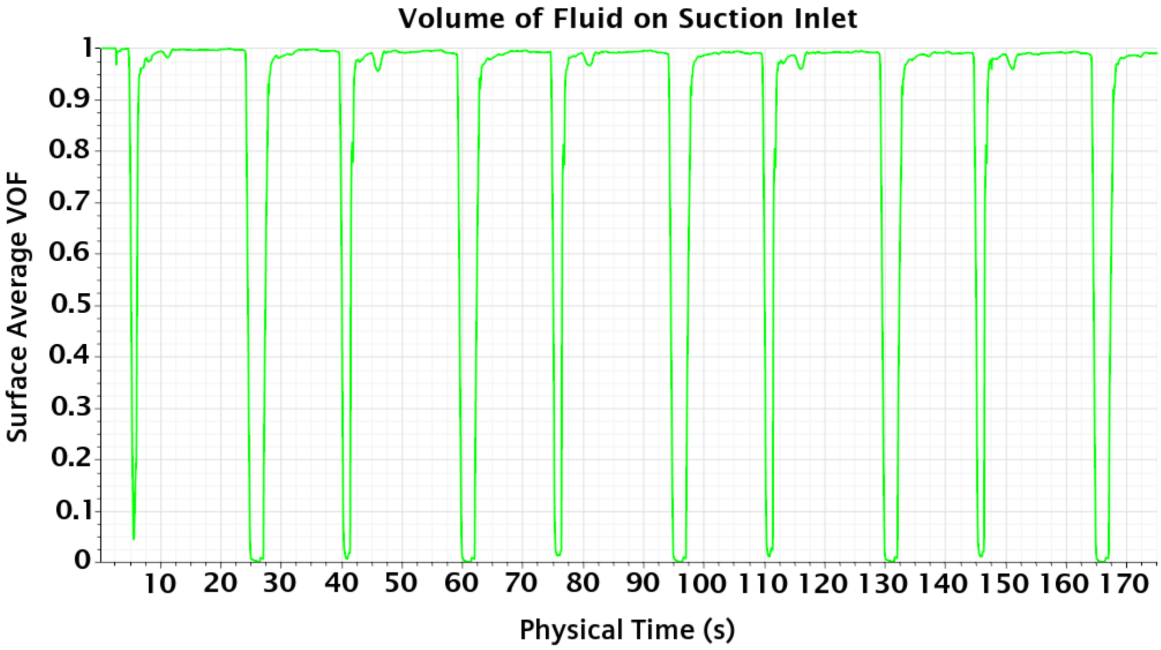

Figure 5-9. Case 6; surface average VoF of oil at suction inlet

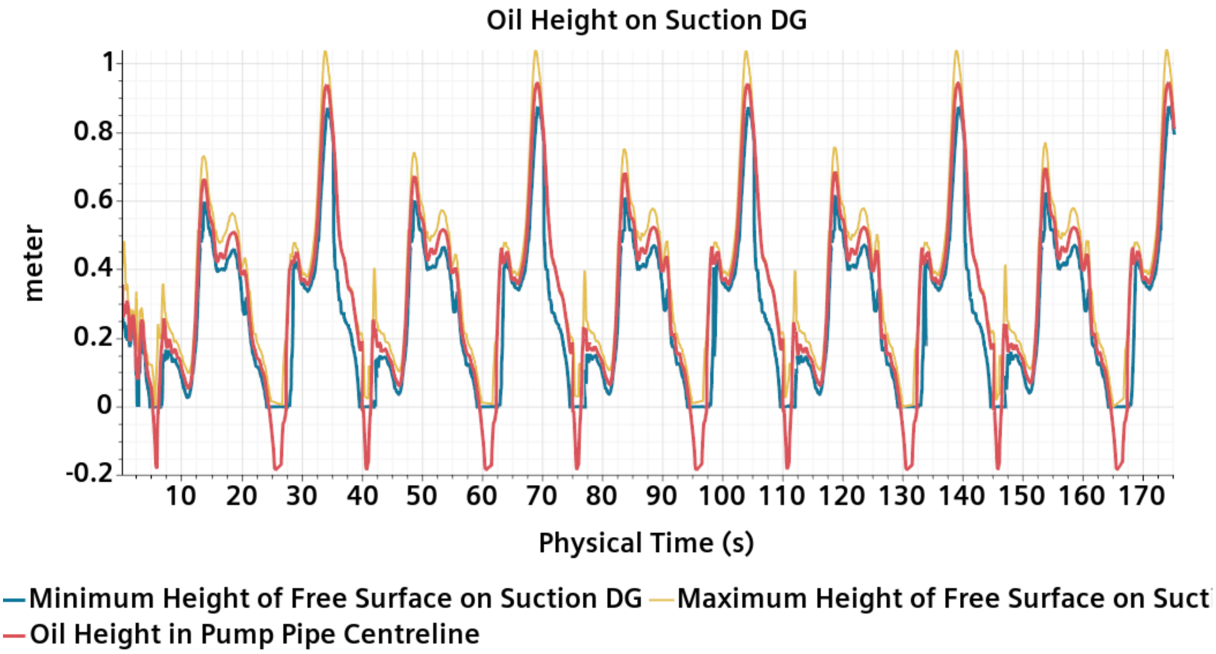

Figure 5-10. Case 6; oil height in suction pipe

Figure 5-11 presents the oil's distribution in the tank at an instance when the suction pipe inlet is completely exposed to air.

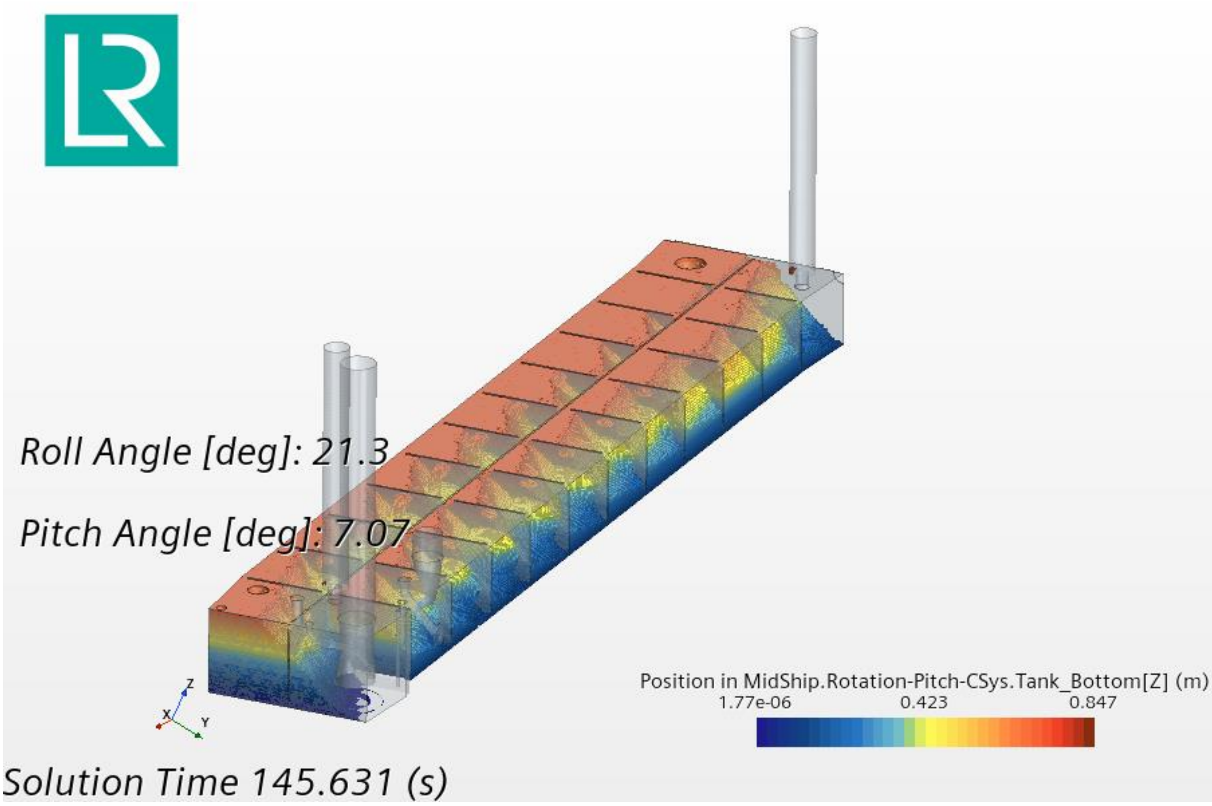

Figure 5-11. Case 6; oil height based on oil threshold

5.2.3 Case 7

Figure 5-12 presents the surface average VoF of oil at the suction pipe inlet. It is observed that the VoF drops to zero periodically. The inlet gets exposed in sets of two with the events occurring approximately 15s apart. The next set of two events occurs approximately 37s later. Figure 5-13 presents the oil height in the pipe based on the free surface monitors. The same behaviour is observed with events happening in sets of two. The oil height drops below the inlet level and as low as the tank bottom. When the surface average VoF drops to zero, the oil height monitors are zero too and the height monitor on the centreline is below zero. This indicates a fully exposed inlet. There are two instances when the surface average VoF is approximately 30% and 7%. These are instances when the inlet is partially exposed to air as also seen by the oil height monitors at the corresponding times.

Figure 5-14 presents the oil's distribution in the tank at an instance when the suction pipe inlet is completely exposed to air.

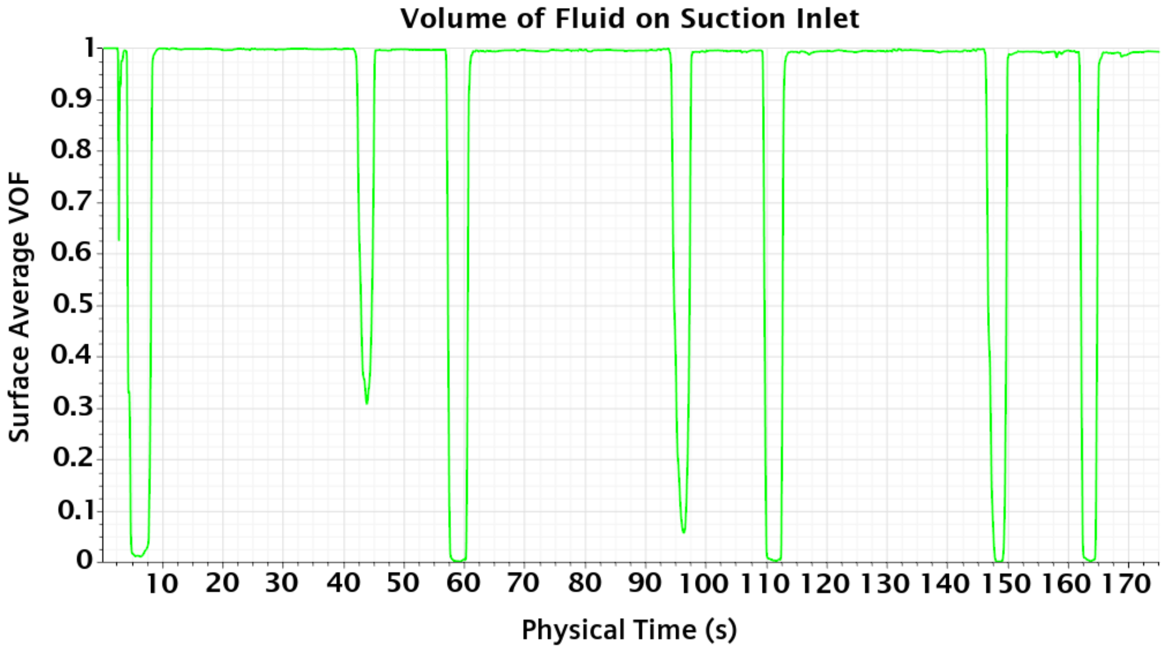

Figure 5-12. Case 7; surface average VoF of oil at suction inlet

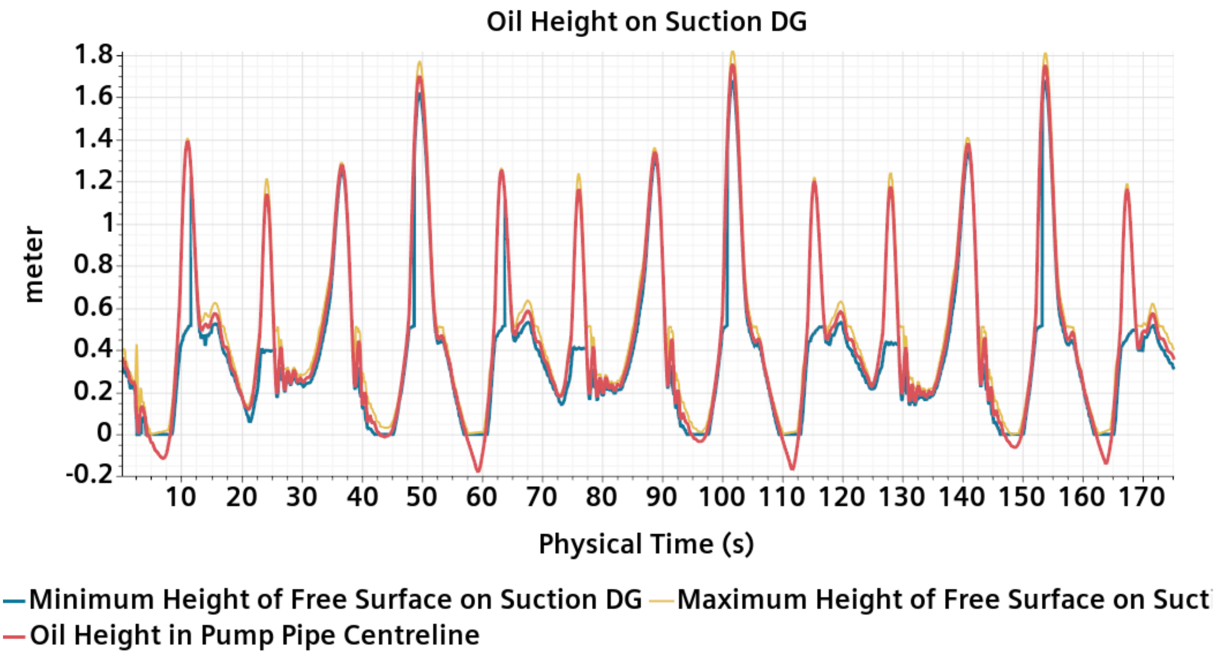

Figure 5-13. Case 7; oil height in suction pipe

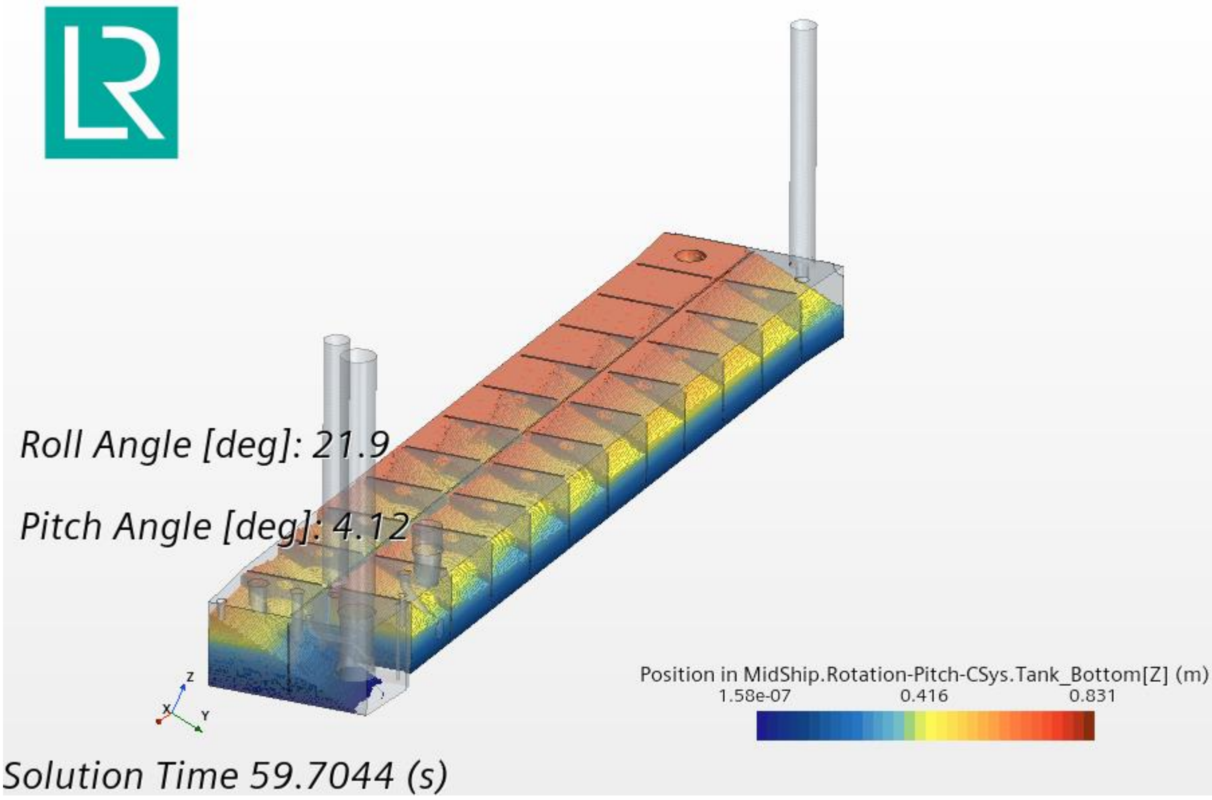

Figure 5-14. Case 7; oil height based on oil threshold

5.2.4 Case 8

Figure 5-15 presents the surface average VoF of oil at the suction pipe inlet. It is observed that the VoF remains constant at 1, indicating that the inlet is fully immersed. Figure 5-16 presents the oil height in the pipe based on the free surface monitors. It is shown that the minimum oil height is approximately 0.15m from the inlet.

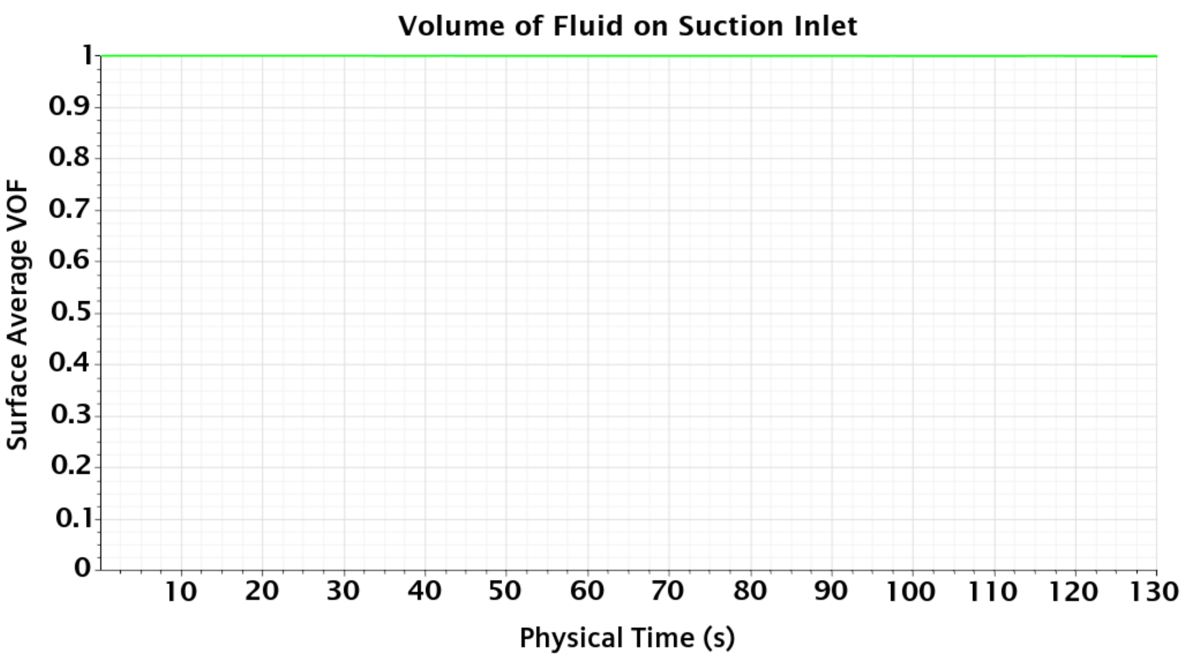

Figure 5-15. Case 8; surface average VoF of oil at suction inlet

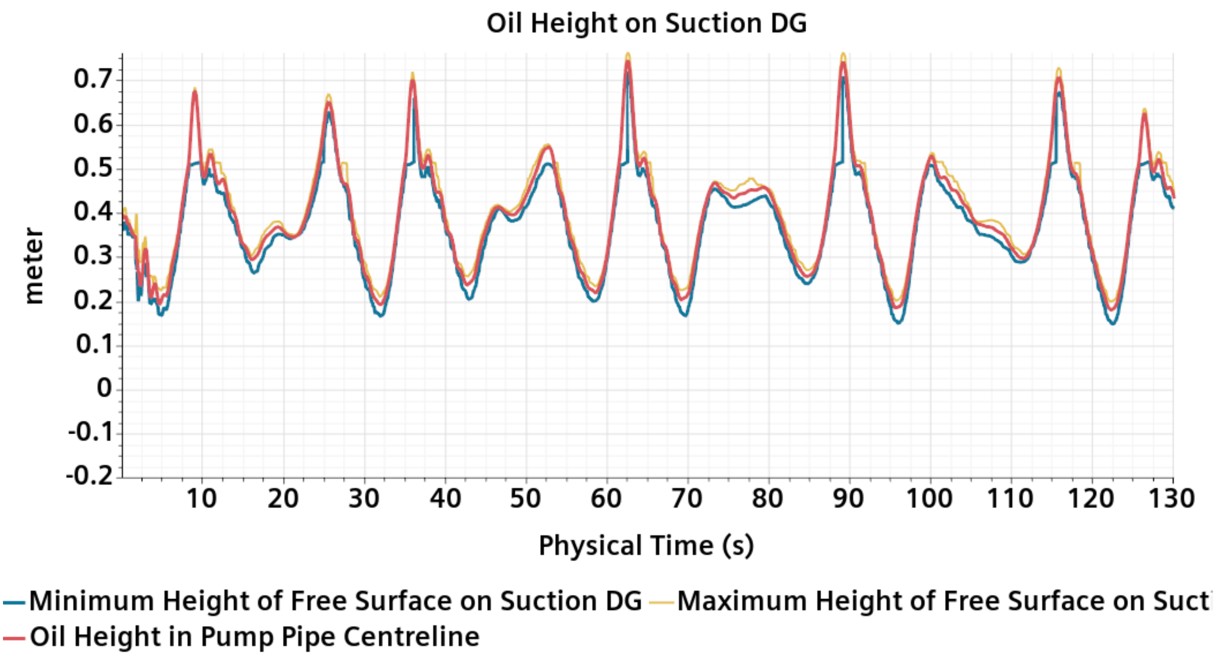

Figure 5-16. Case 8; oil height in suction pipe

Figure 5-17 presents the oil's distribution in the tank at an instance when the suction pipe inlet is completely exposed to air.

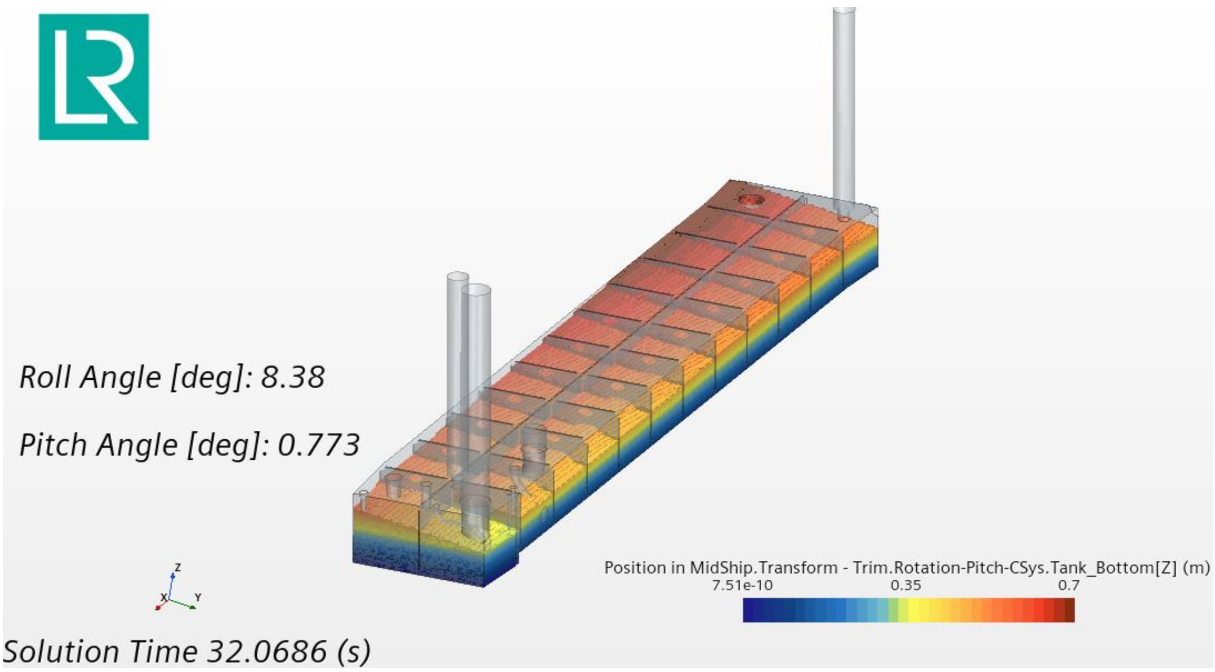

Figure 5-17. Case 8; oil height based on oil threshold

5.2.5 Case 9

Figure 5-18 presents the surface average VoF of oil at the suction pipe inlet. It is observed that the VoF remains constant at 1, indicating that the inlet is fully immersed in oil at all times. Figure 5-19 presents the oil height in the pipe based on the free surface monitors. It is shown that the minimum oil height is approximately 0.26m from the inlet.

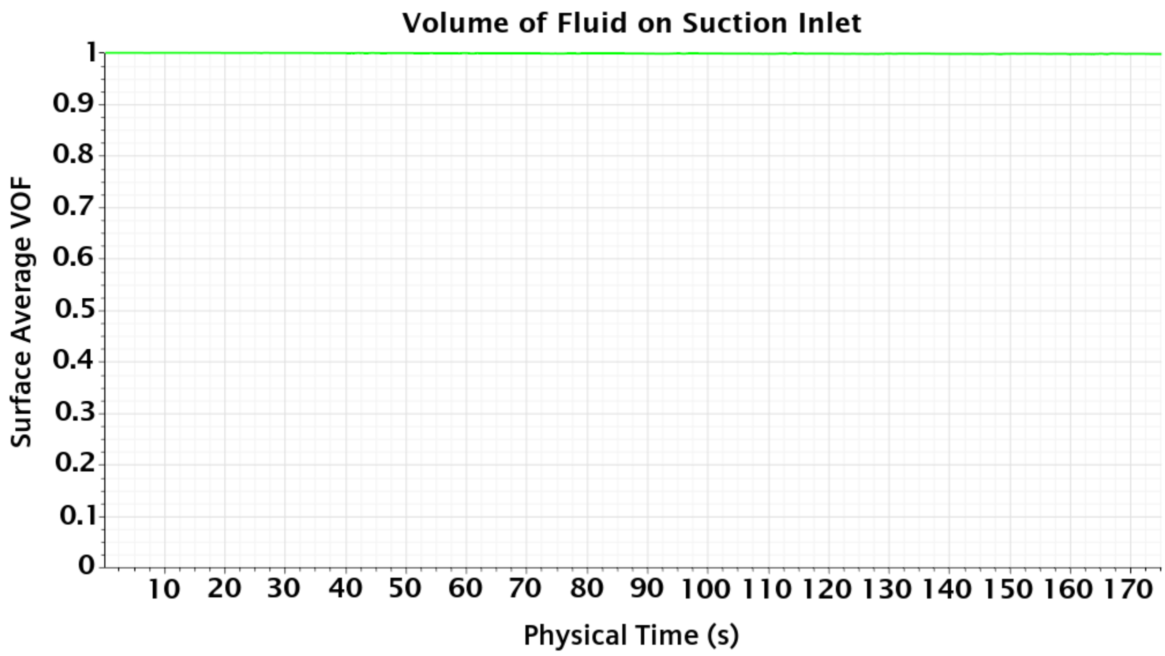

Figure 5-18. Case 9; surface average VoF of oil at suction inlet

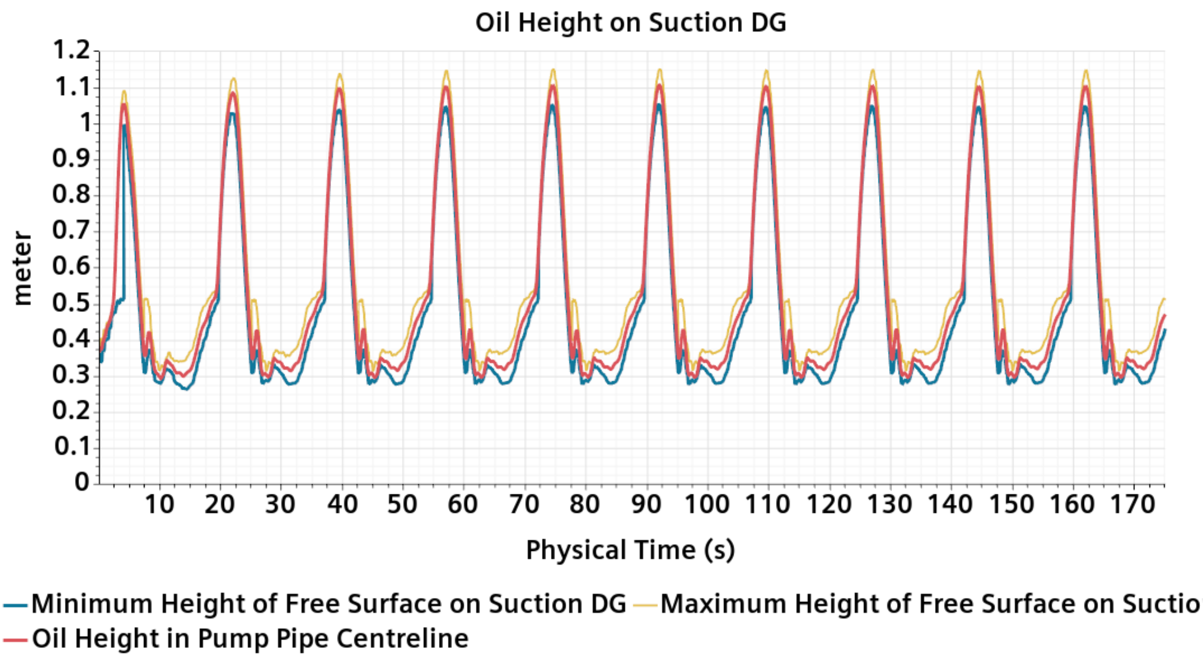

Figure 5-19. Case 9; oil height in suction pipe

5.3 Irregular Motions

5.3.1 Case 10

Figure 5-20 presents the surface average VoF for the duration of the simulation. There are nineteen (19) instances where the VoF dips significantly, even as low as zero. The start and end times of each event are shown in the figures in Appendix B.1.

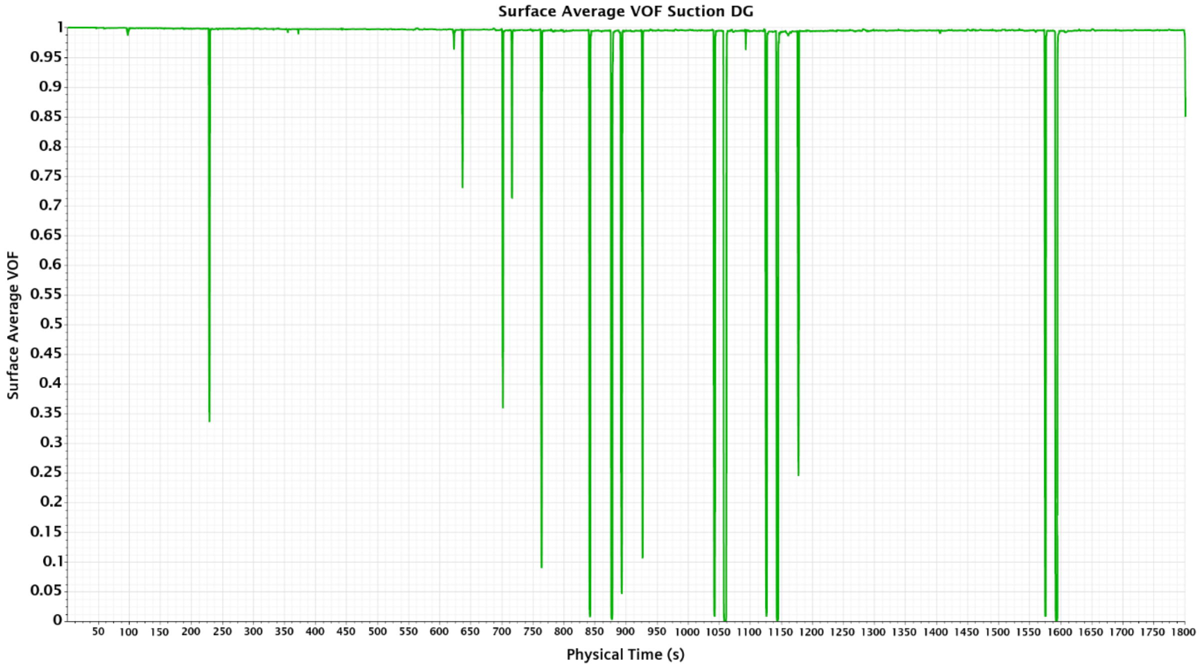

Figure 5-20. Case 10; surface average VoF of oil at suction inlet

The oil height is shown in Figure 5-21. It is observed that there are instances the maximum and the minimum free surface heights are zero (meaning there is no free surface in the pipe to monitor) and the oil height at the centreline is also zero or below. This combination of values, along with the surface average VoF being zero, indicates the inlet is fully exposed to air. However, there are other instances where the minimum free surface height is zero, the oil height in the centreline is also at zero or below but the maximum free surface height is above zero. This combination of values indicates that the inlet is partly exposed to air and the surface average VoF shows the amount of the inlet area that is exposed to air. This is graphically seen in Figure 5-22 which shows the oil height in the pipe overlaid with the surface average VoF.

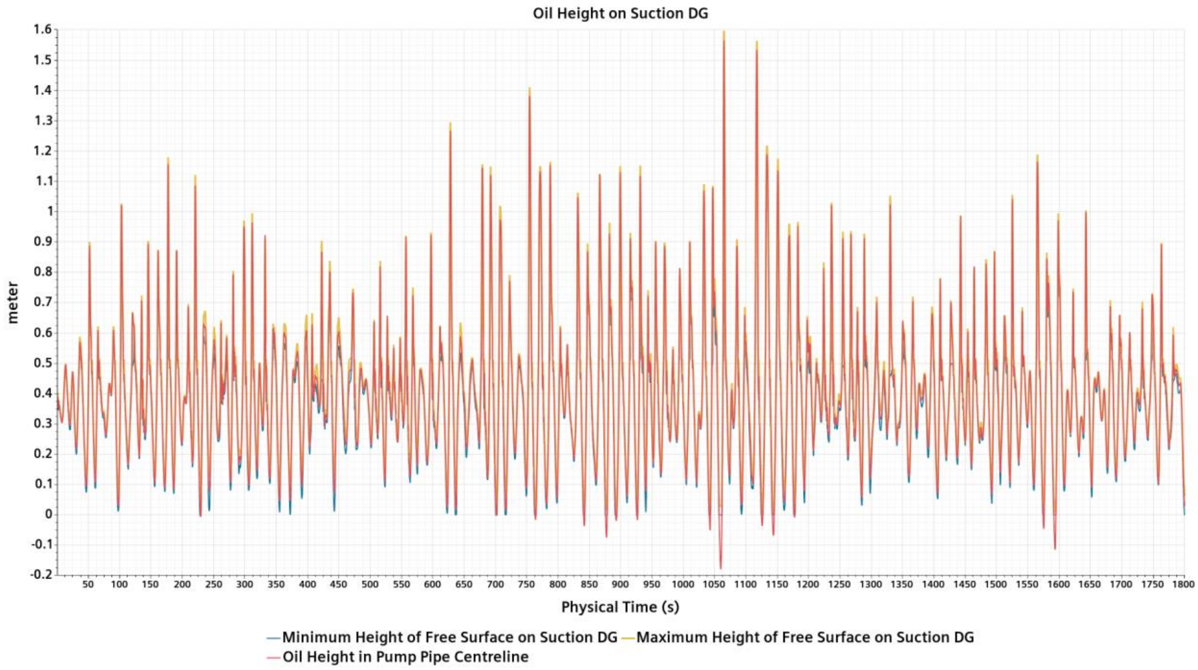

Figure 5-21. Case 10; oil height in suction pipe

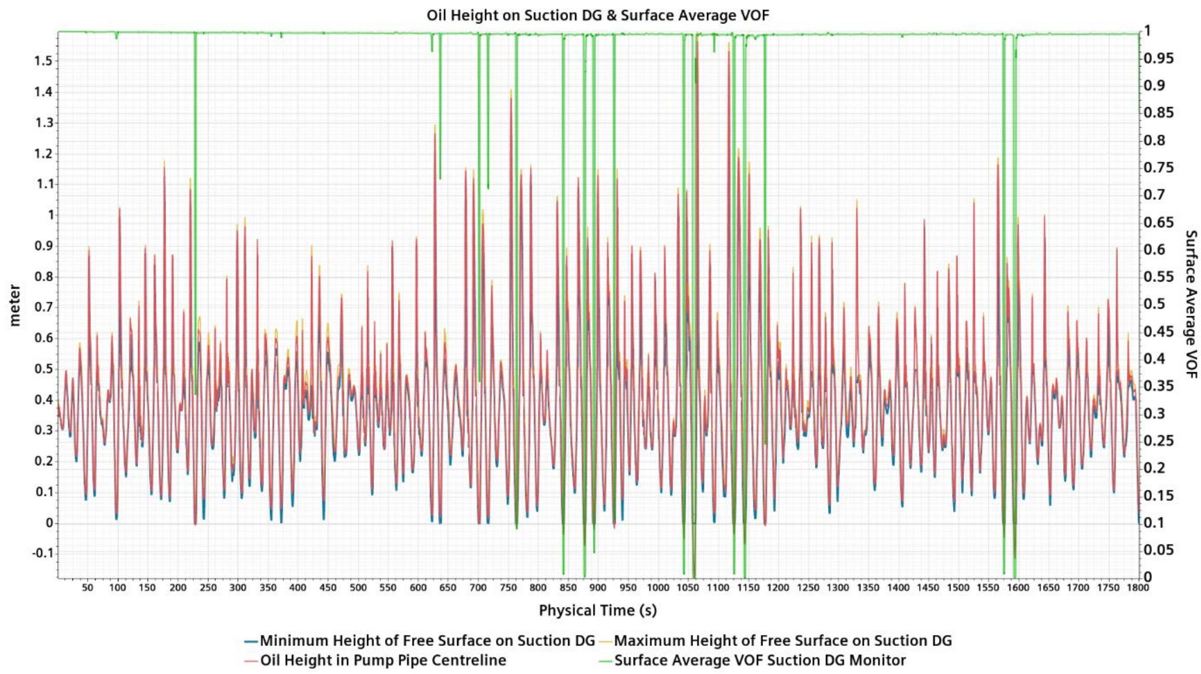

Figure 5-22. Case 10; Oil height and surface average VoF

Figure 5-23 and Figure 5-24 present the surface average VoF overlaid with the rotation and translation motions in an effort to identify whether one motion type or the other have a more pronounced effect on the surface average VoF. Based on these plots, it was decided to investigate the same scenario with the translation motions deactivated (paragraph 5.3.2, below).

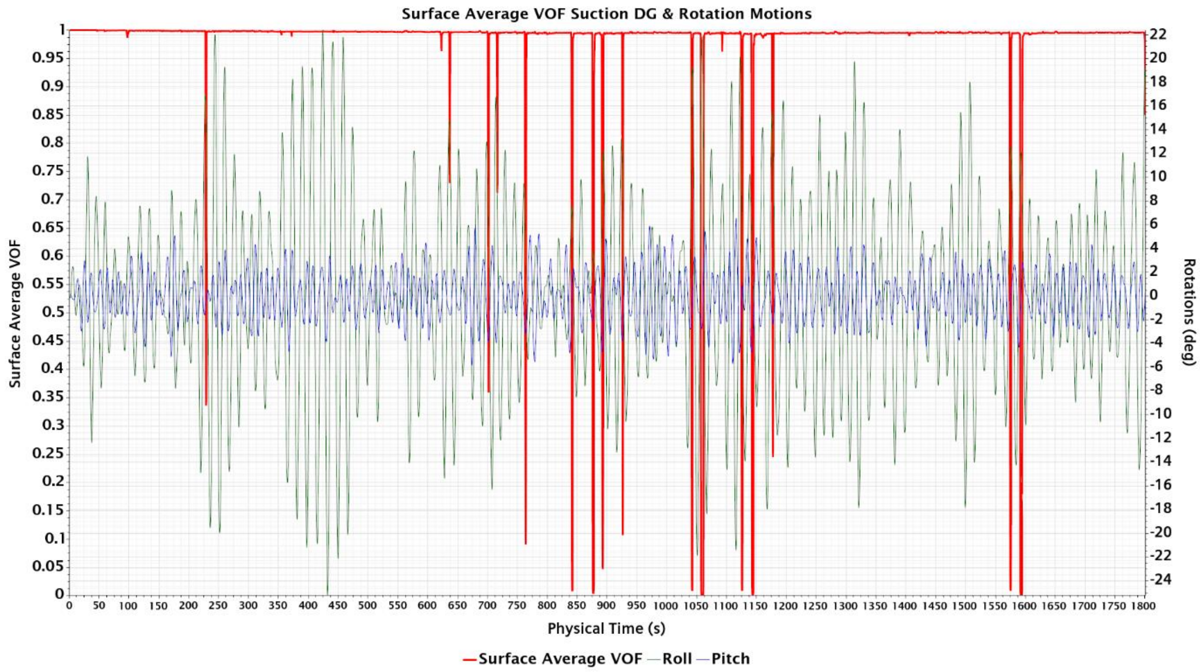

Figure 5-23. Case 10; Surface average VoF and rotations

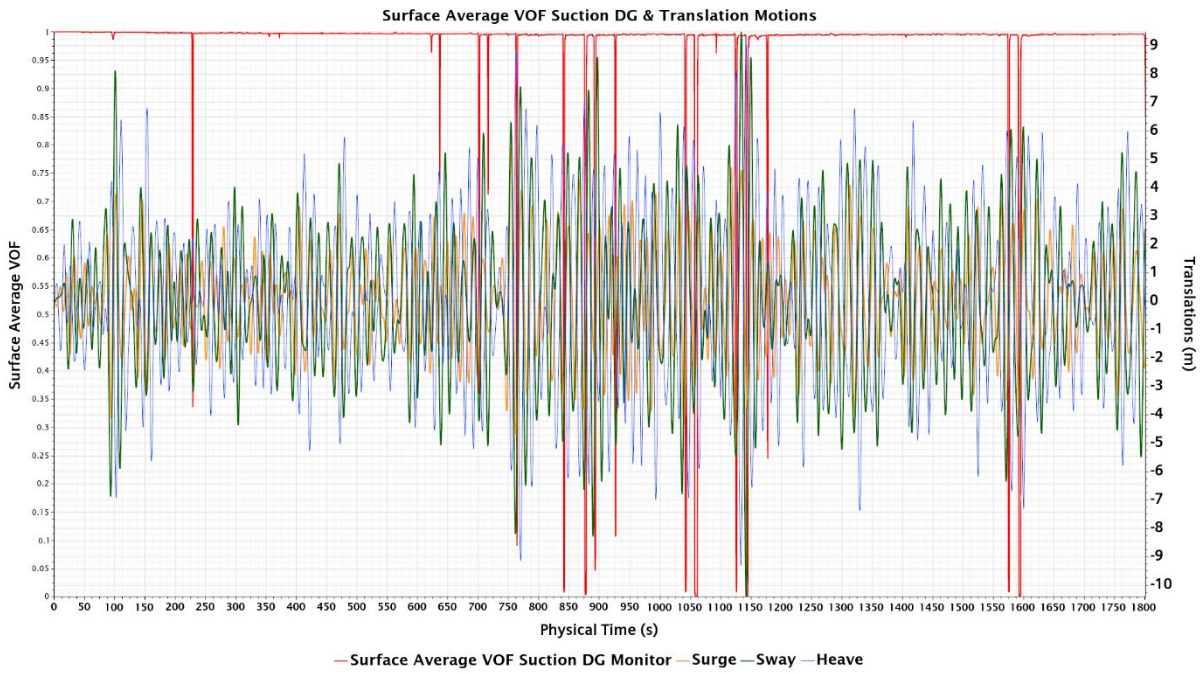

Figure 5-24. Case 10; Surface average VoF and translations

5.3.2 Case 11

Figure 5-25 shows the surface average VoF at the inlet surface. In this case, with the translation motions deactivated, seven events are observed. Their start and end times can be seen in the figures in Appendix B.2. Looking at the oil height inside the pipe in Figure 5-26, it is observed that there are instances when the minimum oil surface height is very close to zero and at the same time the surface average VoF plot (Figure 5-25) does not present any significant drop-off on the VoF. This indicates that the inlet is immersed in oil but only by a small margin. At other times, the minimum free surface height is zero with only a minor drop in surface average VoF which means that the inlet is partially exposed. This is better demonstrated in Figure 5-27 which presents the oil height overlaid with the surface average VoF. It is also seen that there is another event driving the oil height to zero at the end of the simulation. The severity and extent of the event are unknown, but it is evident (Figure 5-26) that at least the minimum oil surface height is below zero. Combined with the observation that the surface average VoF is decreasing rapidly below 1 as shown in Figure 5-25, this is an indication of an at least partially exposed inlet.

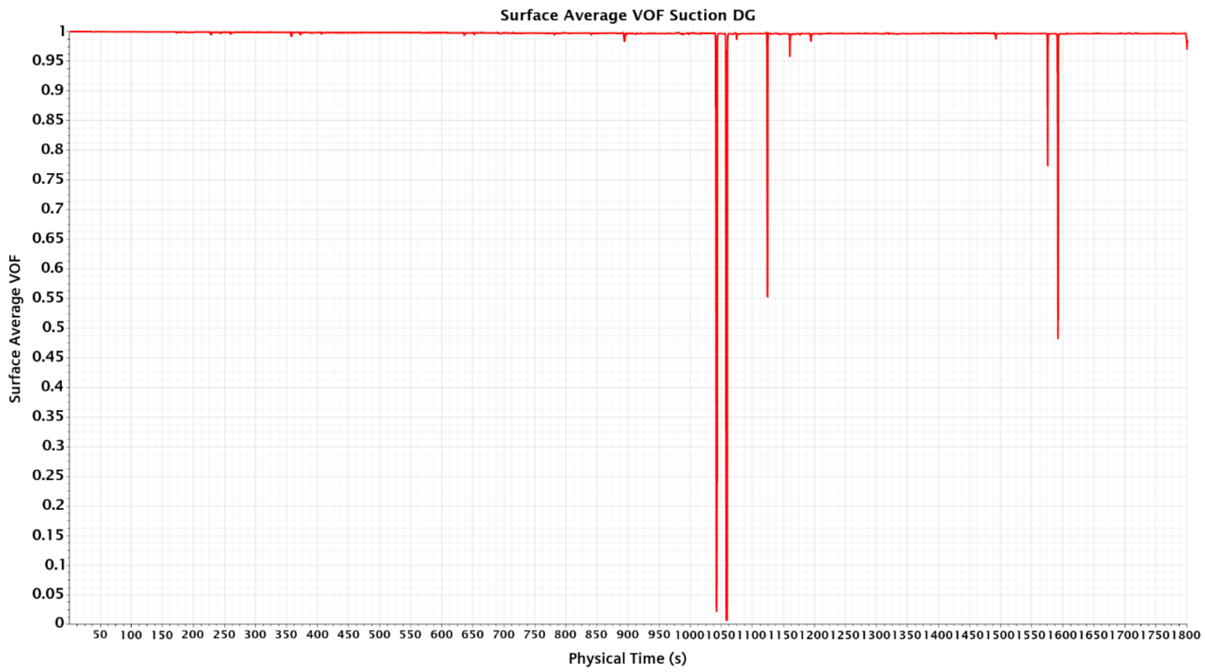

Figure 5-25. Case 11; surface average VoF of oil at suction inlet

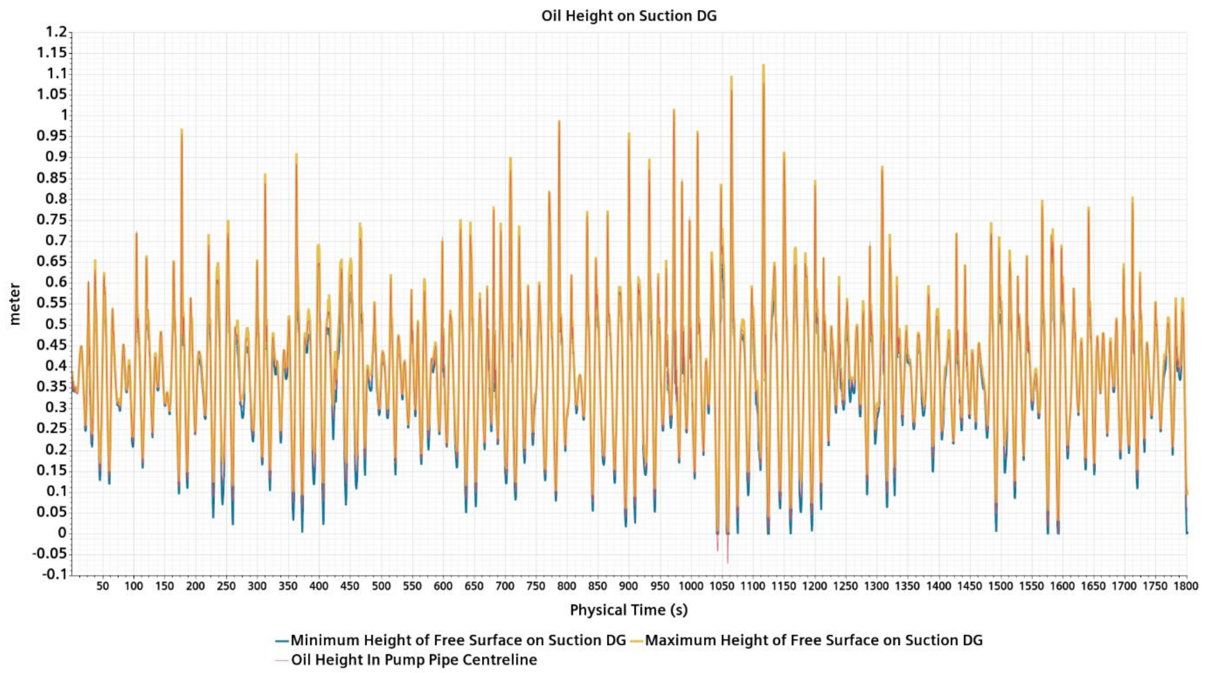

Figure 5-26. Case 11; oil height in suction pipe

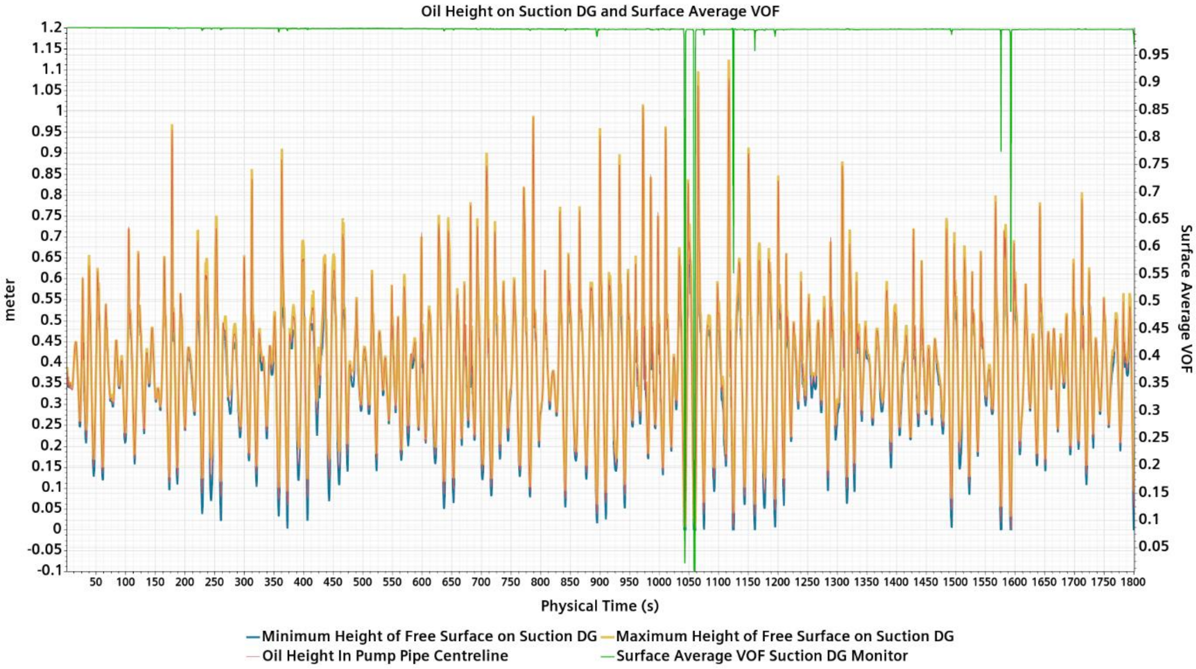

Figure 5-27. Case 11; oil height and surface average VoF

5.3.3 Case 12

Six instances were identified where the surface average VoF at the suction inlet decreases, three of which result in zero values (Figure 5-28) indicating a fully exposed inlet. The start and end times of the instances are shown in the figures in Appendix B.3. The maximum and minimum surface oil height along with the oil height at the centreline of the pipe are shown in Figure 5-29. Figure 5-30 shows the correlation of the oil height in the pipe with the surface average VoF.

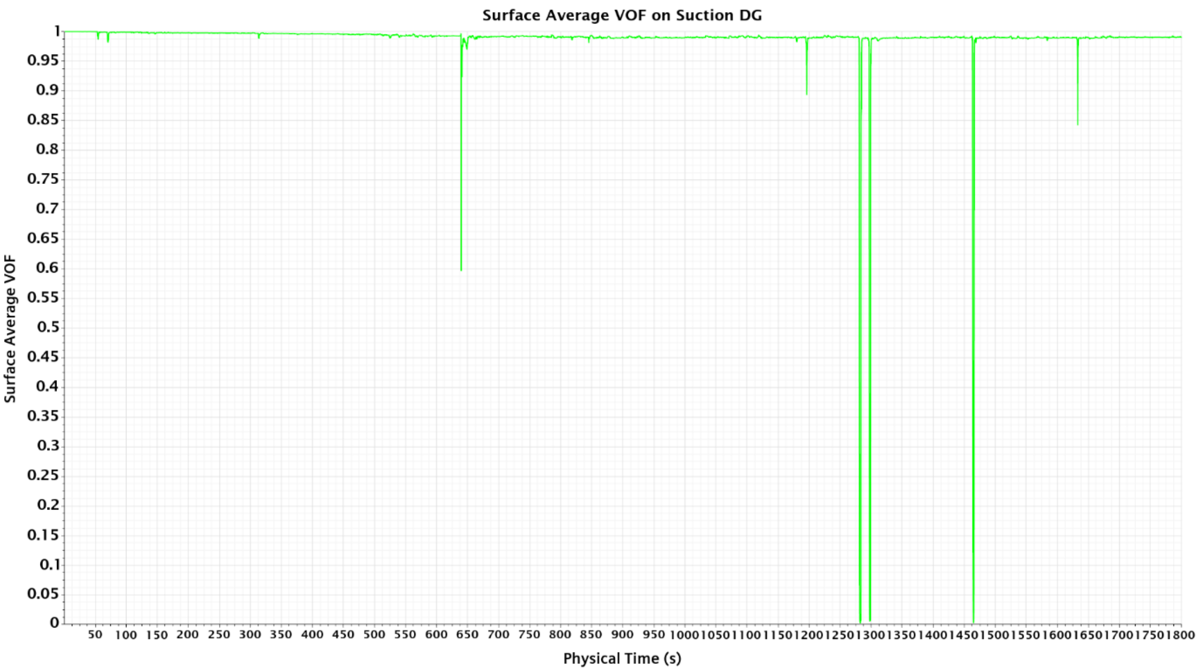

Figure 5-28. Case 12; surface average VoF of oil at suction inlet

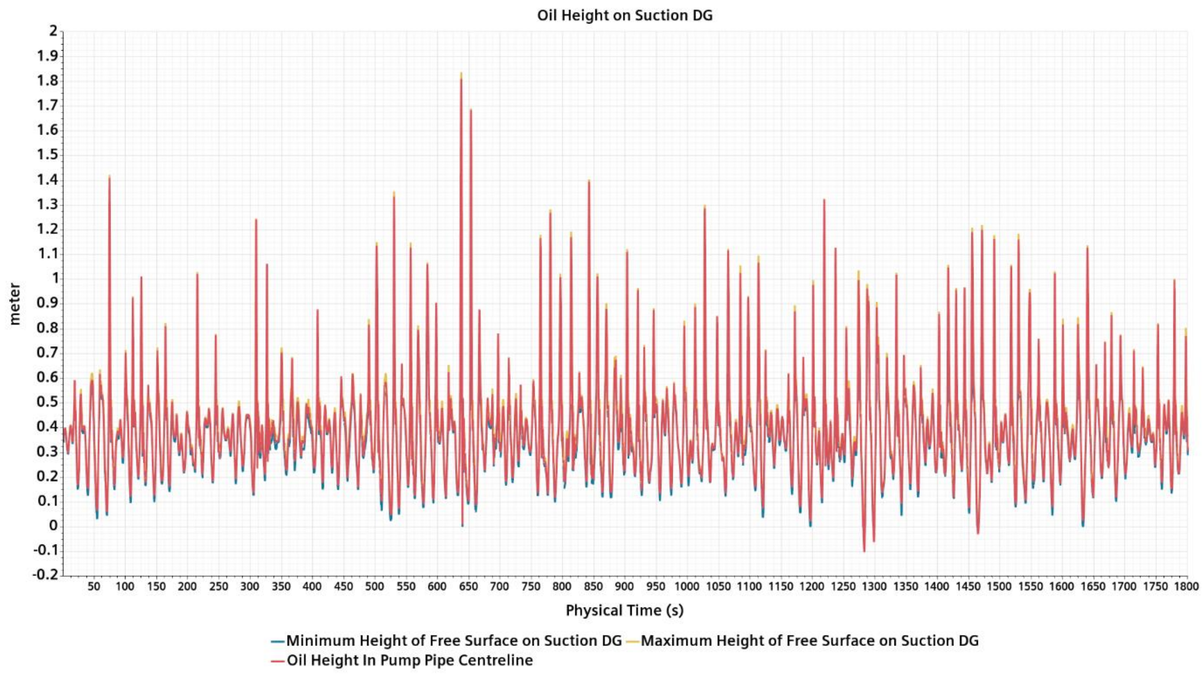

Figure 5-29. Case 12; oil height in suction pipe

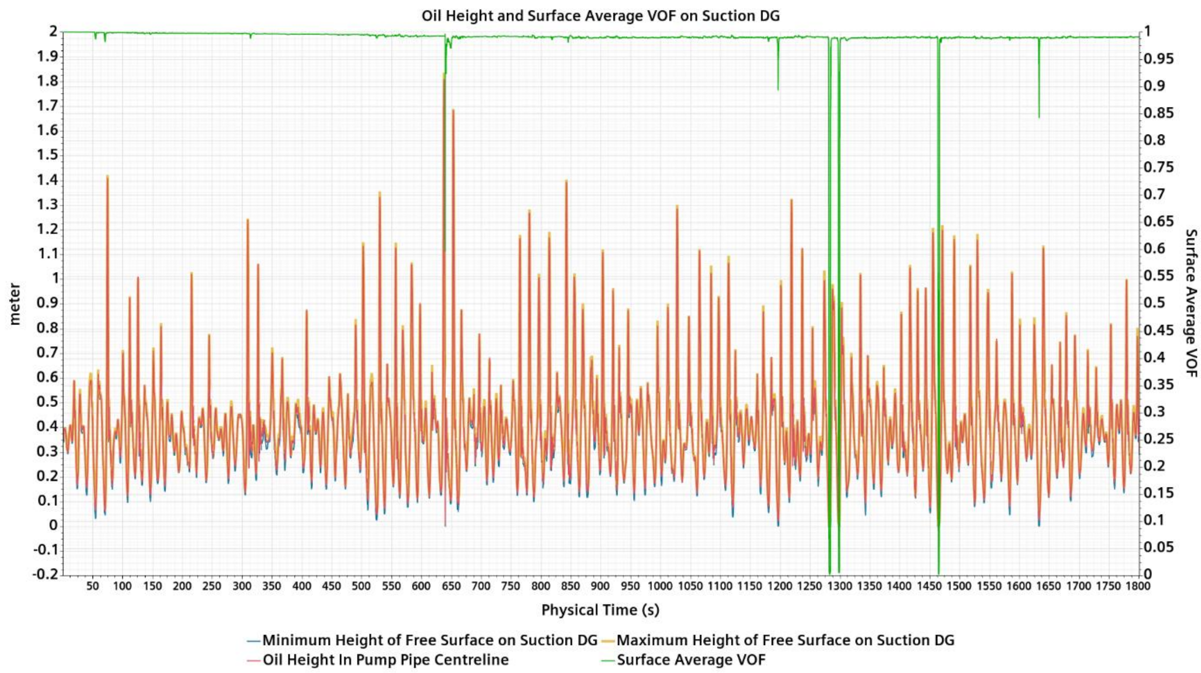

Figure 5-30. Case 12; oil height and surface average VoF

5.3.4 Case 13

Case 13 was repeated with the translation motions deactivated. In this case, there is one instance when the surface average VoF (Figure 5-31) drops to zero. At that time, in Figure 5-32 it is shown that the free surface minimum height is zero and the oil height at the centreline of the pipe is below zero. This indicates that the inlet is at least partially exposed to air. This is also seen in Figure 5-33 where the oil height is overlaid with the surface average VoF. It is observed that there is a second instance when the minimum free surface height is zero but the oil height in the centreline and maximum free surface oil height are above zero. This coincides with a very small drop of the surface average VoF indicating a marginally exposed inlet. The start and end times of these instances are shown in Appendix B.4.

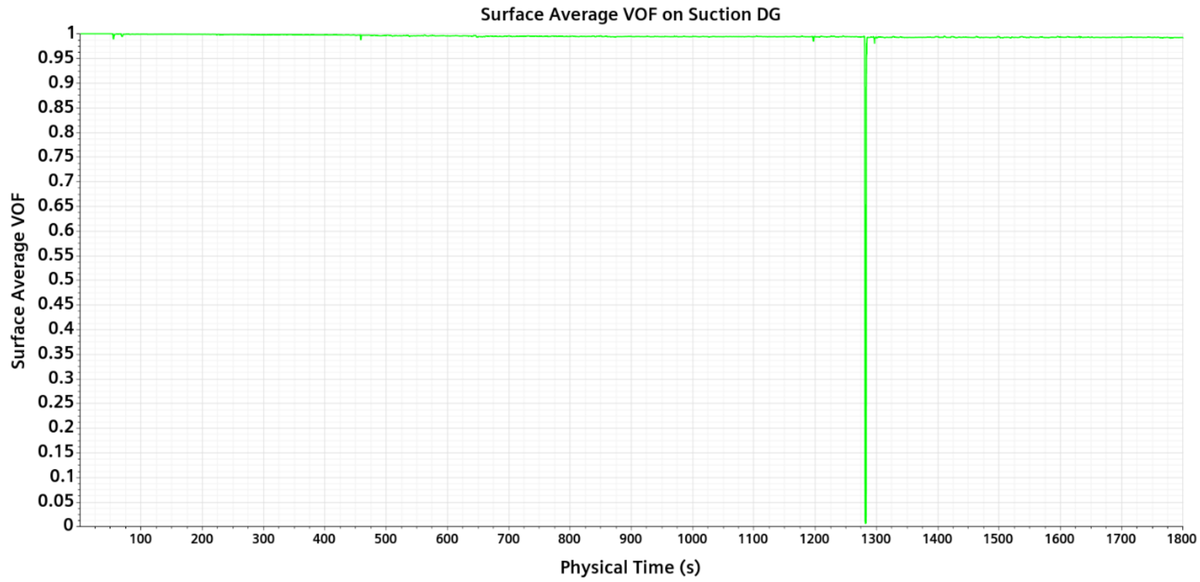

Figure 5-31. Case 13; surface average VoF of oil at suction inlet

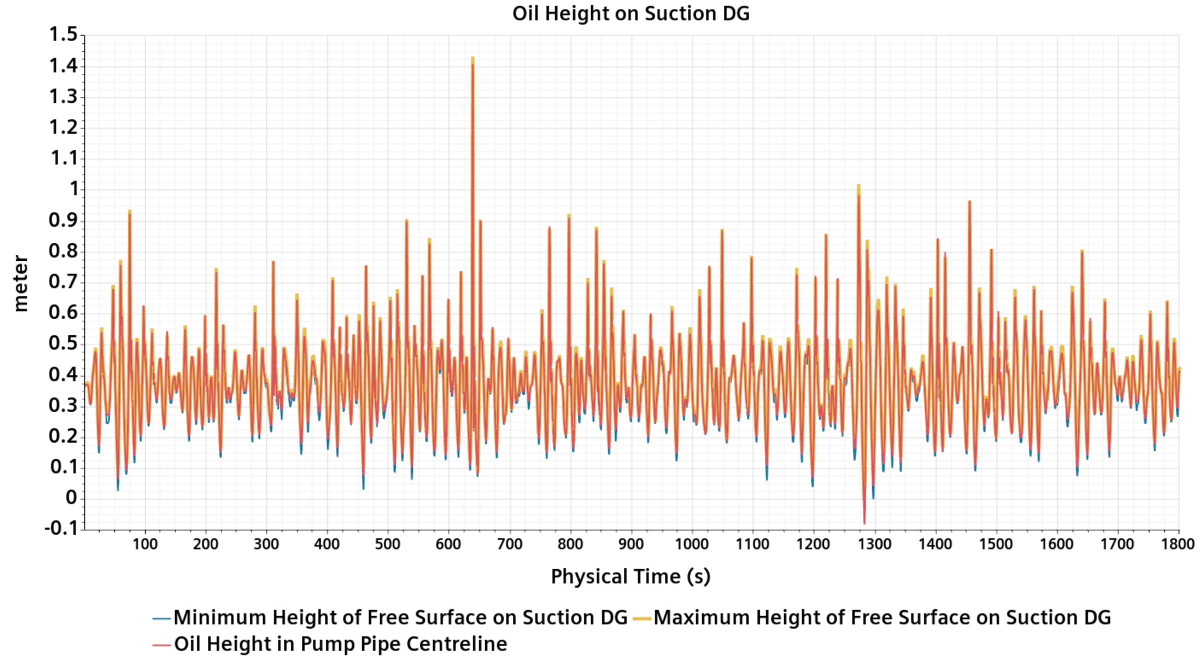

Figure 5-32. Case 13; oil height in suction pipe

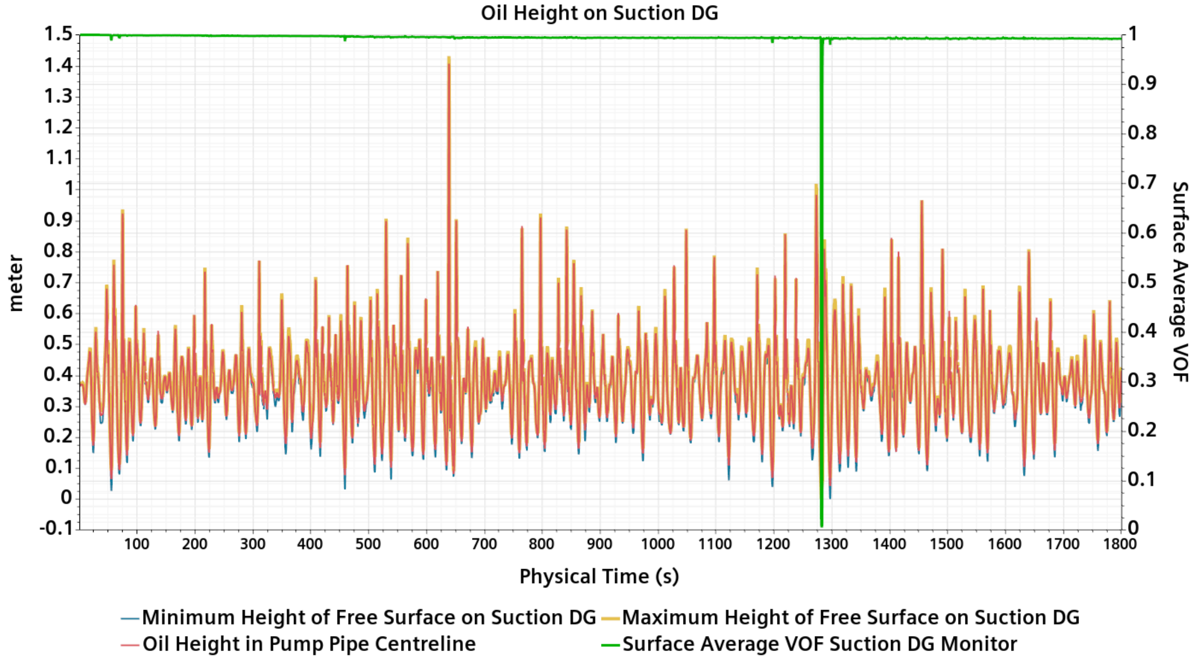

Figure 5-33. Case 13; oil height and surface average VoF

5.4 Incident Motions

5.4.1 Case 14

Based on the surface average VoF in Figure 5-34 and the oil height in the pipe shown in Figure 5-35, there are four events where the inlet is at least partially exposed to air. Figure 5-36 shows the correlation between the surface average VoF and the oil height in the pipe.

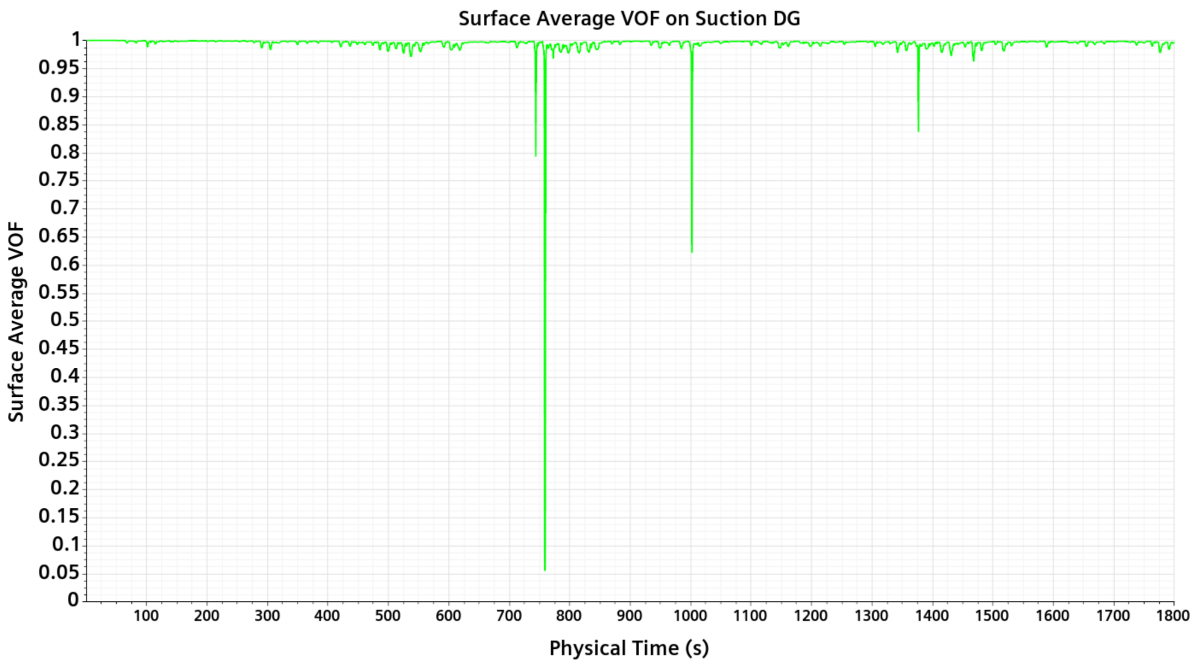

Figure 5-34. Case 14; surface average VoF of oil at suction inlet

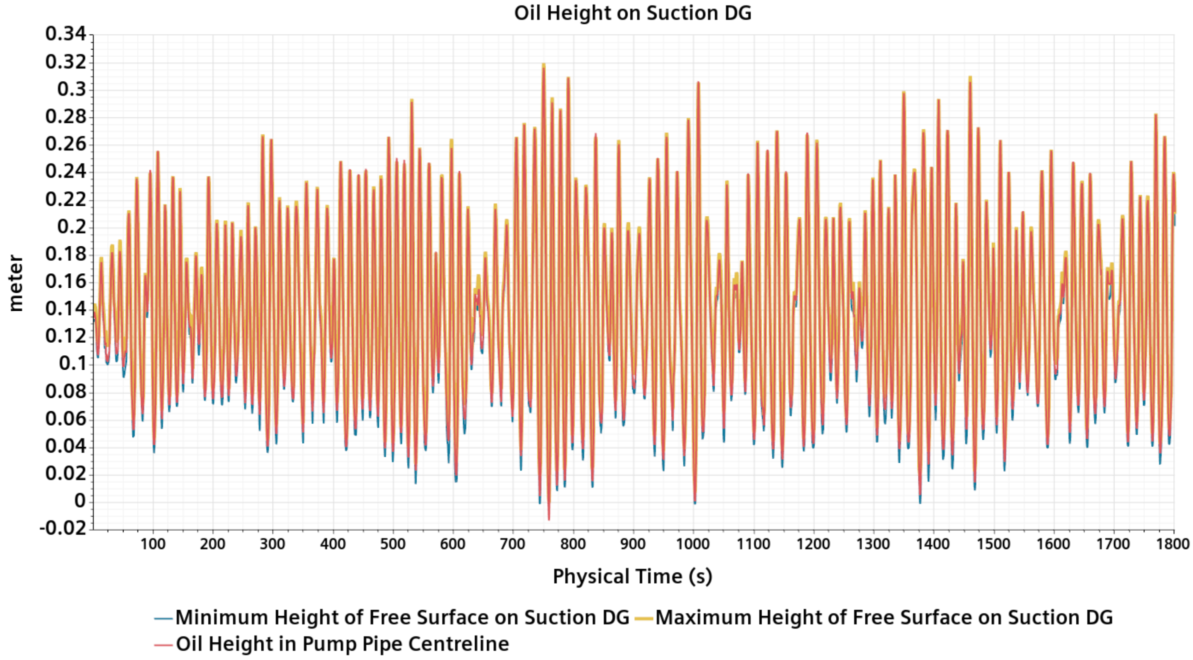

Figure 5-35. Case 14; oil height in suction pipe

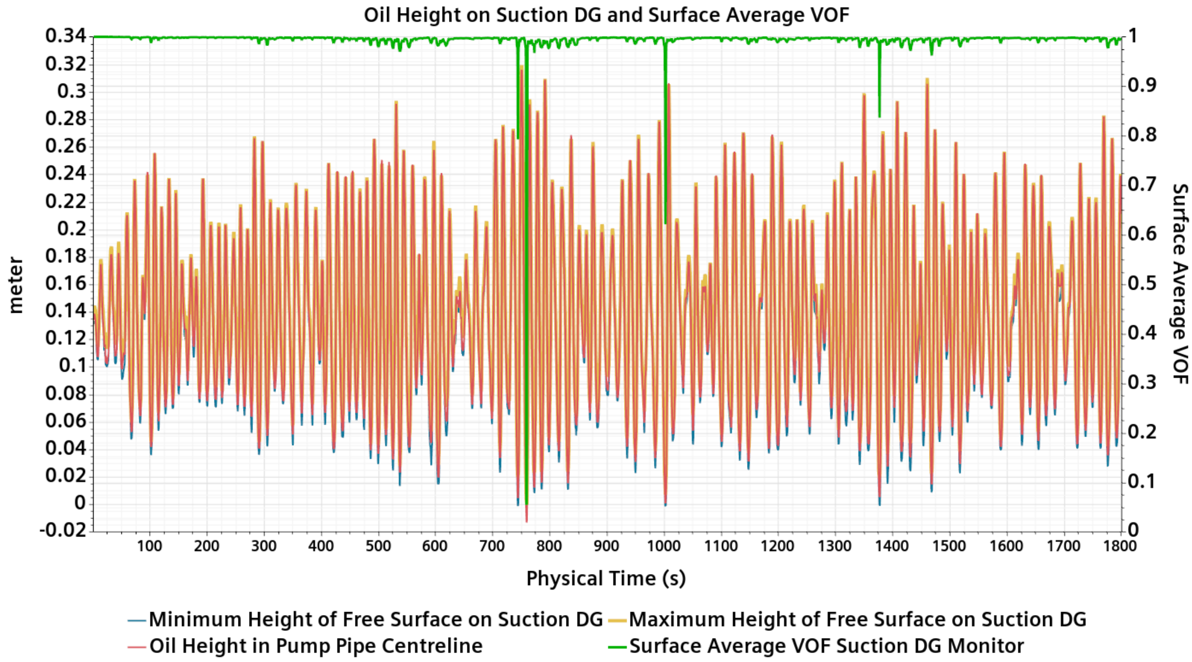

Figure 5-36. Case 14; oil height and surface average VoF

5.4.2 Case 15

Figure 5-37 shows the surface average VoF and Figure 5-38 presents the oil height in the suction pipe. It is seen when the translation motions are deactivated, the inlet is immersed at all times for the duration of the simulation.

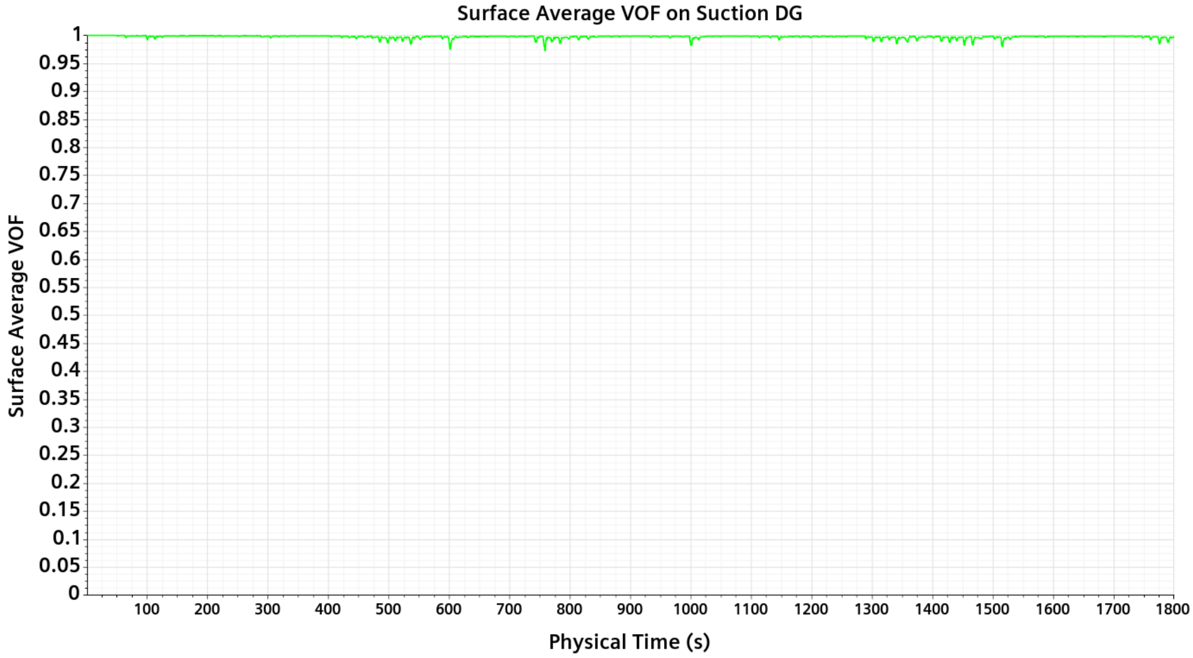

Figure 5-37. Case 15; surface average VoF of oil at suction inlet

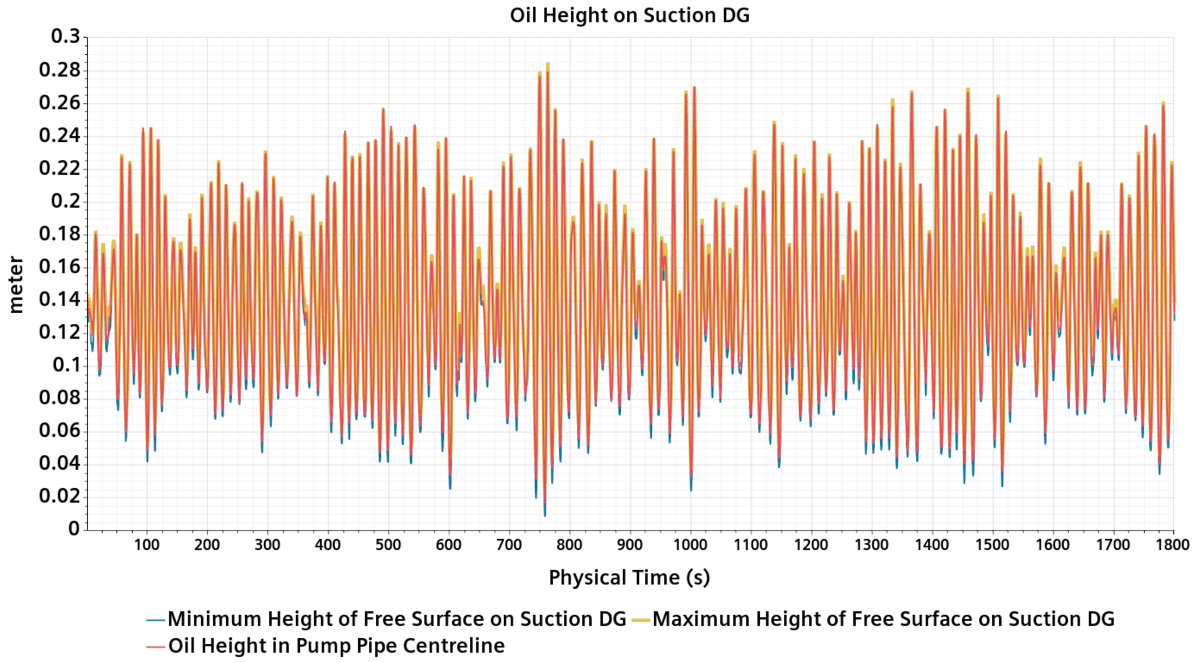

Figure 5-38. Case 15; oil height in suction pipe

5.4.3 Case 16

In this case, the surface average VoF (Figure 5-39) is 1 throughout the time history of the simulation and the oil surface height (Figure 5-40) does not go below zero. This means that for this condition, the inlet is immersed in oil throughout the simulation.

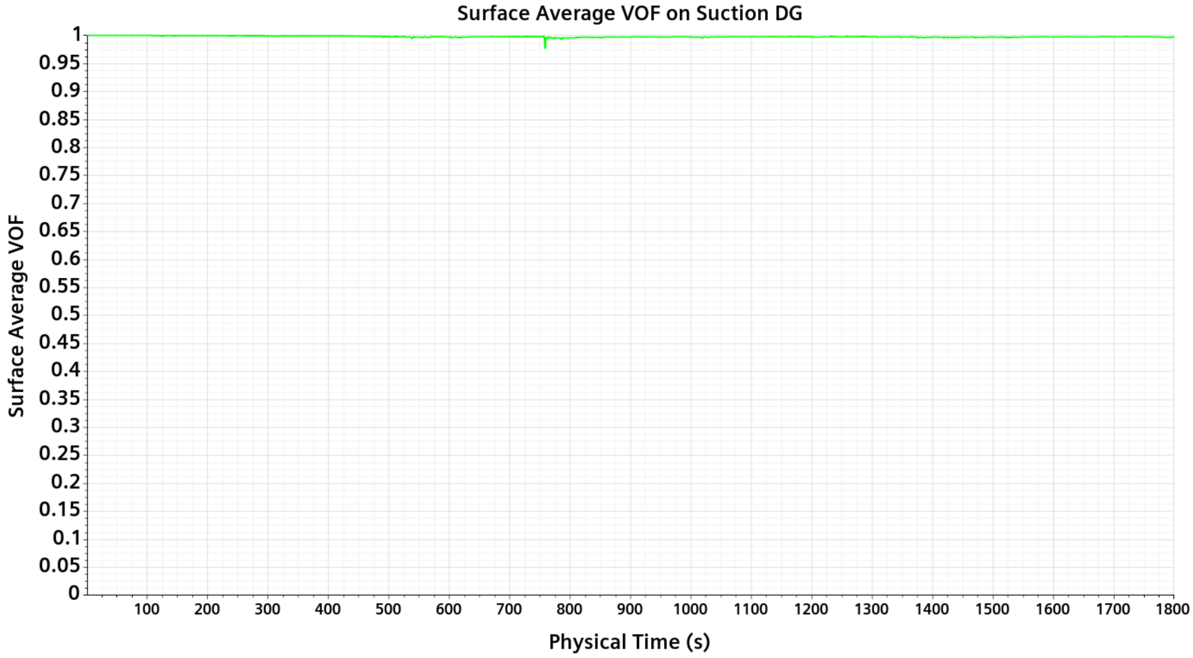

Figure 5-39. Case 16; surface average VoF of oil at suction inlet

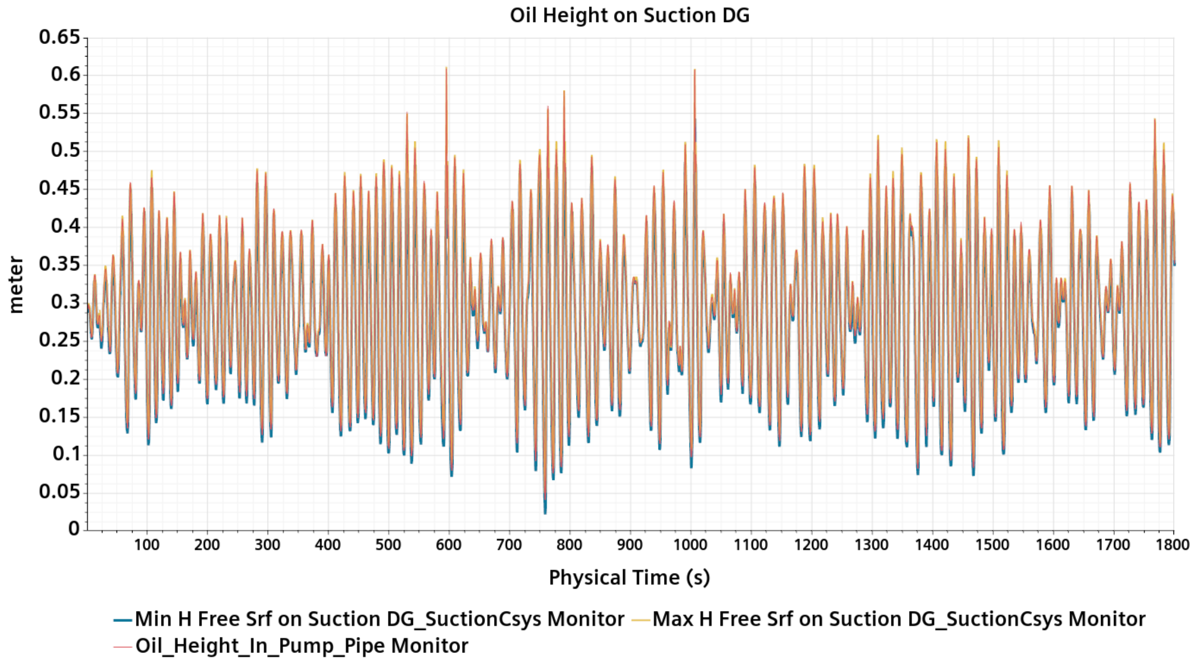

Figure 5-40. Case 16; oil height in suction pipe

5.4.4 Case 17

In this case, the surface average VoF (Figure 5-41) is 1 throughout the time history of the simulation and the oil surface height (Figure 5-42) does not go below zero. This means that for this condition, the inlet is immersed in oil throughout the simulation.

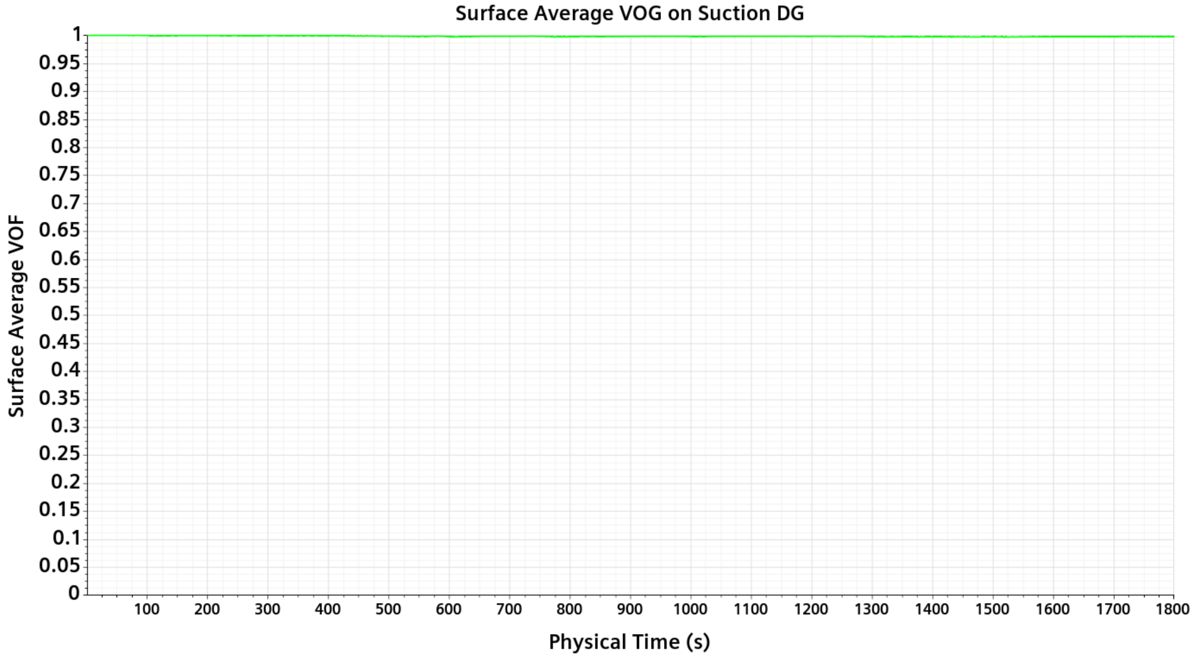

Figure 5-41. Case 17; surface average VoF of oil at suction inlet

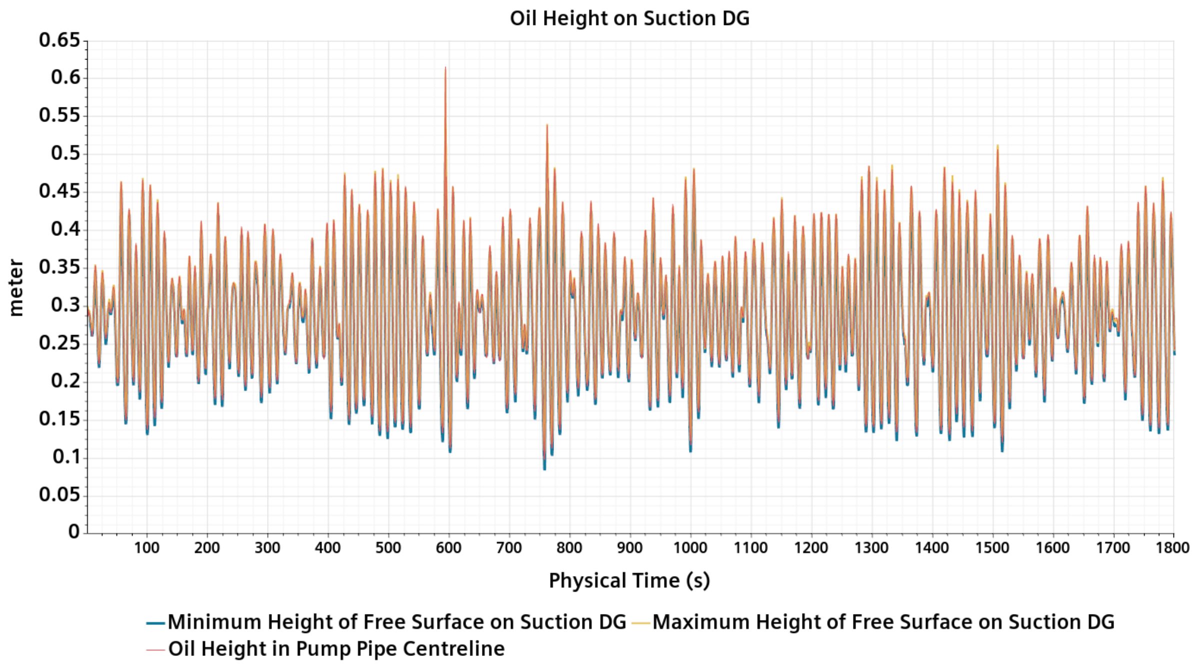

Figure 5-42. Case 17; oil height in suction pipe

5.4.5 Case 18

In this case, the surface average VoF (Figure 5-43) is 1 throughout the time history of the simulation and the oil surface height (Figure 5-44) does not go below zero. This means that for this condition, the inlet is immersed in oil throughout the simulation.

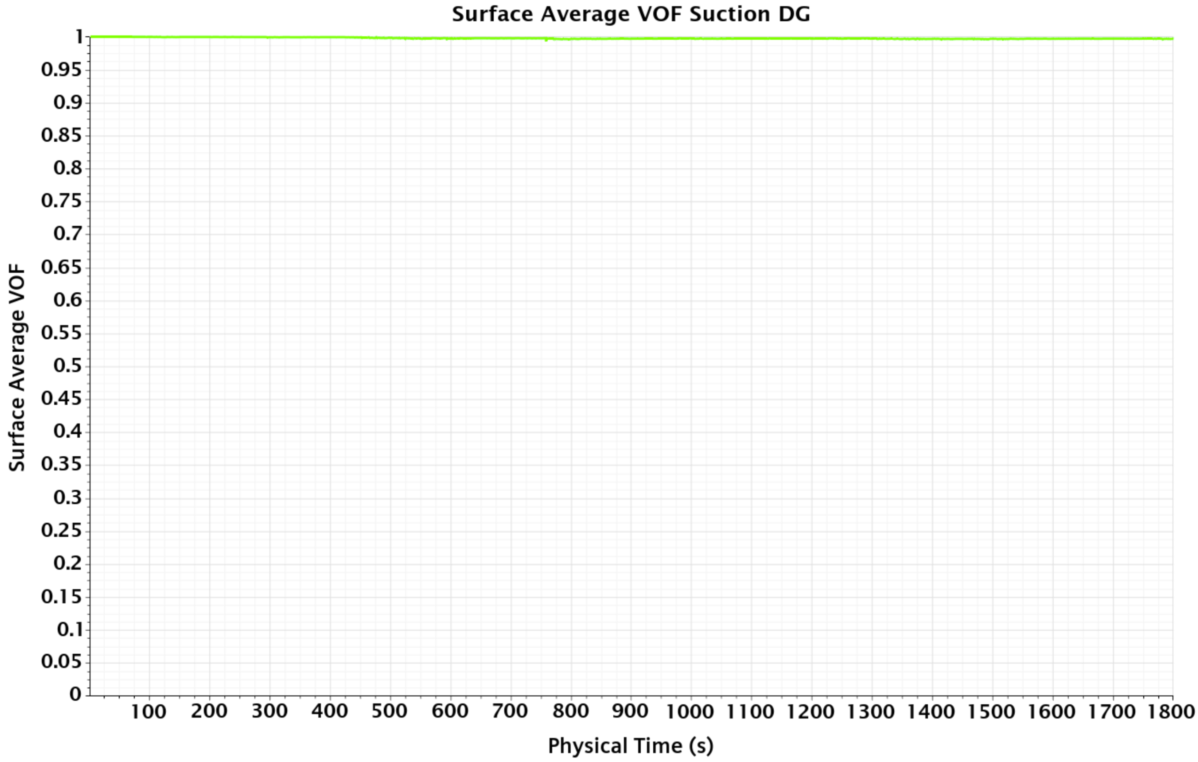

Figure 5-43. Case 18; surface average VoF of oil at suction inlet

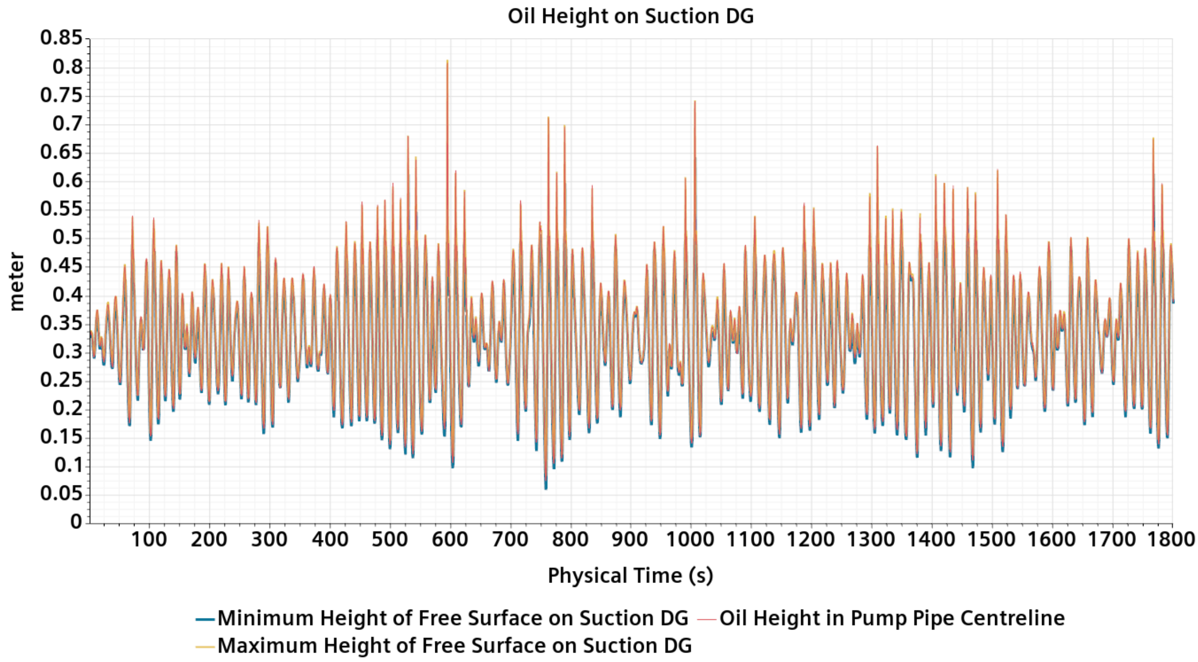

Figure 5-44. Case 18; oil height in suction pipe

6. Conclusions[5]

A total of 18 conditions were simulated including static rotations, regular (sinusoidal) motions and irregular motions. The motions at the time and location of the incident were also simulated. Instances when the oil sump pump inlet was exposed to air were identified for each simulated scenario.

6.1 Recommendation for future work

The circulation of oil (out of the oil sump towards the engine and return to the tank) was not included in the modelling. Future work could take this into account and include it in the modelling.

References

[1] International Maritime Organization (IMO); *International Convention for the Safety of Life At Sea*; Consolidated edition 2004

[2] *Sloshing analysis of Viking Sky Oil Sump N. 05 STBD*; Report No: 2022:OC2021 F-120 Confidential – Vegard Slettahjell Skjefstad - Sintef

[3] *No.34 Standard Wave Data*; 1992, Rev.1 June 2000, Corr. Nov. 2001 - IACS

[4] *RE: Viking Sky CFD Simulation results discussion* – Email correspondence – Norbert Bakkers and Lefteris Kalochristianakis – 12/08/2022

Appendix A Details of the CFD Setup

A.1 Coordinate Systems

The motions were defined with respect to the ship's CG. Three coordinate systems were created to manage the rotations in a cascading manner with the CG coordinate system being at the top of the hierarchy. Each coordinate system was a child of the previous one and at the top of the coordinate systems tree was the CG coordinate system (Figure A-1). The final node at the bottom of the tree, is a coordinate system located at the suction pump inlet for monitoring purposes.

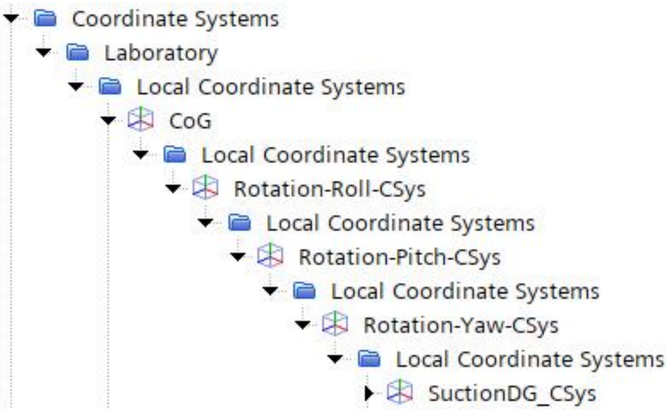

Figure A-1. Coordinate systems

A.2 Motions Implementation in StarCCM+

The motions of the oil sump were set up as translations with superposed rotations. The parent motion was the translation which managed the coordinate system for the roll (Figure A-2). The order of rotations was roll-pitch-yaw and each rotation managed the coordinate system of the child rotation. The motions tree is presented in Figure A-3. The last rotation (yaw) managed the coordinate system located at the suction pump inlet. It was ensured that the axis direction, axis origin, rotation angle and managed coordinate systems were set correctly for the corresponding rotation (Figure A-4).

Translation - Properties ×	
Properties	
Translation Velocity	[${Vx}, ${Vy}, ${Vz}]
Coordinate System	Laboratory->CoG
Managed Coordinate Systems	[Laboratory->CoG->Rotation-Roll-CSys]

Figure A-2. Translation motion setup

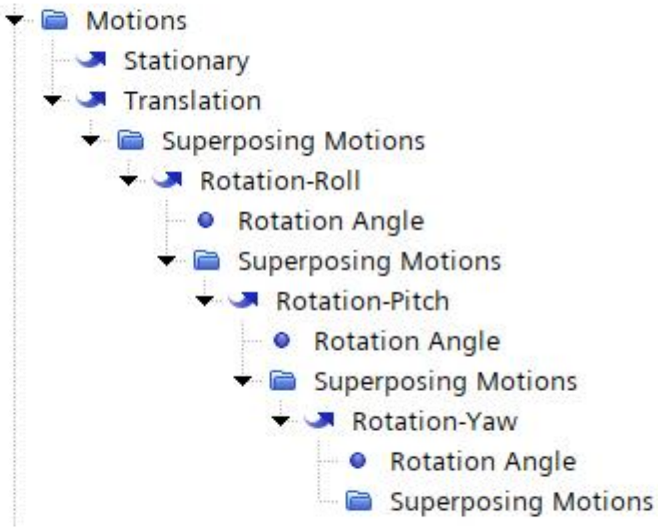

Figure A-3. Motions defined in StarCCM+

Rotation-Yaw - Properties ×	
▾Properties	
Axis Direction	[0.0, 0.0, 1.0]
Axis Origin	[0.0, 0.0, 0.0] m
Rotation Specification	Rotation Angle
Coordinate System	Laboratory->CoG->Rotation-Roll-CSys->Rotation-Pitch-CSys->Rotation-Yaw-CSys
Managed Coordinate Systems	[Laboratory->CoG->Rotation-Roll-CSys->Rotation-Pitch-CSys->Rotation-Yaw-CSys->SuctionDG_CSys

Figure A-4. Definition of yaw motion

A.3 Monitors

The surface average VoF is used to identify whether the inlet is exposed to the air or not. Surface average VoF is the sum of the volume of fluid (oil in this case) contained in each cell located at the inlet surface, averaged over the surface area (Equation A-1Error! Reference source not found.). This measure gives an indication of the surface area that is covered by oil.

$$Surface\ Average\ \equiv \frac{1}{a}\int \varphi da = \frac{\sum_f \varphi_f A_f}{\sum_f A_f}$$

Equation A-1. Surface average definition

Surface average VoF of 1 (or 100%) denotes a surface that is fully covered with oil. Surface average VoF of 0 (or 0%) means that there is no oil on the surface. An intermediate value, for example 0.6 (or 60%) implies that the surface is 60% covered with oil and therefore 40% open to air (since air is the only other fluid in the simulation).

Appendix B Event Durations

B.1 Case 10

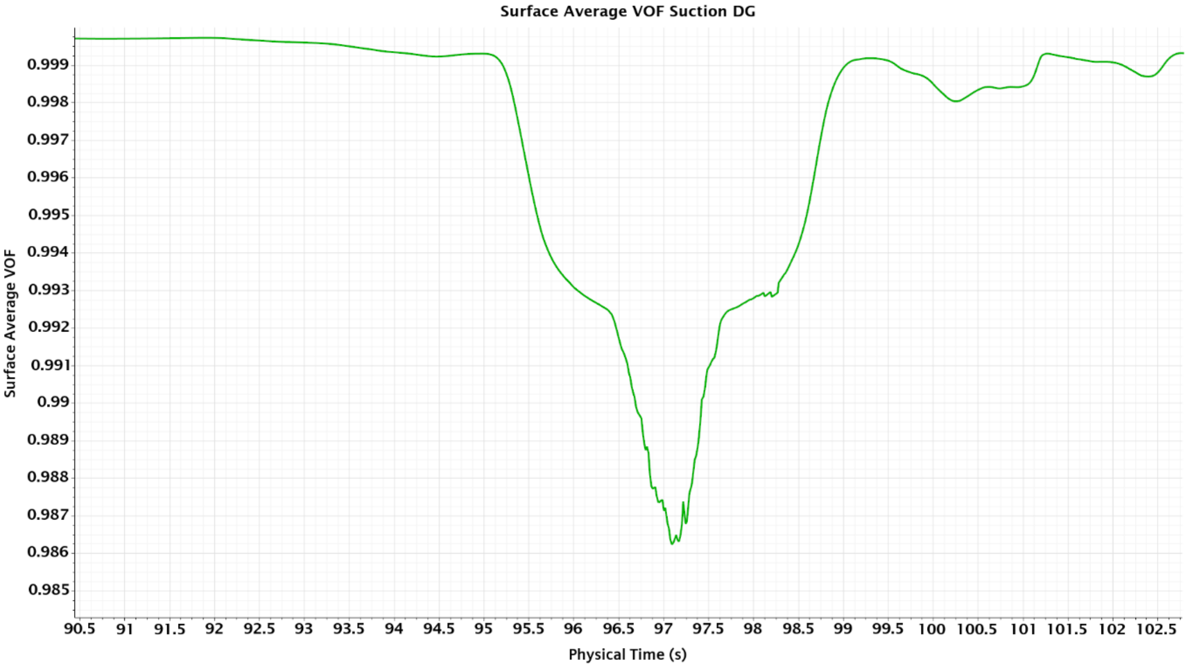

Figure B-5. Case 10; duration of event 1

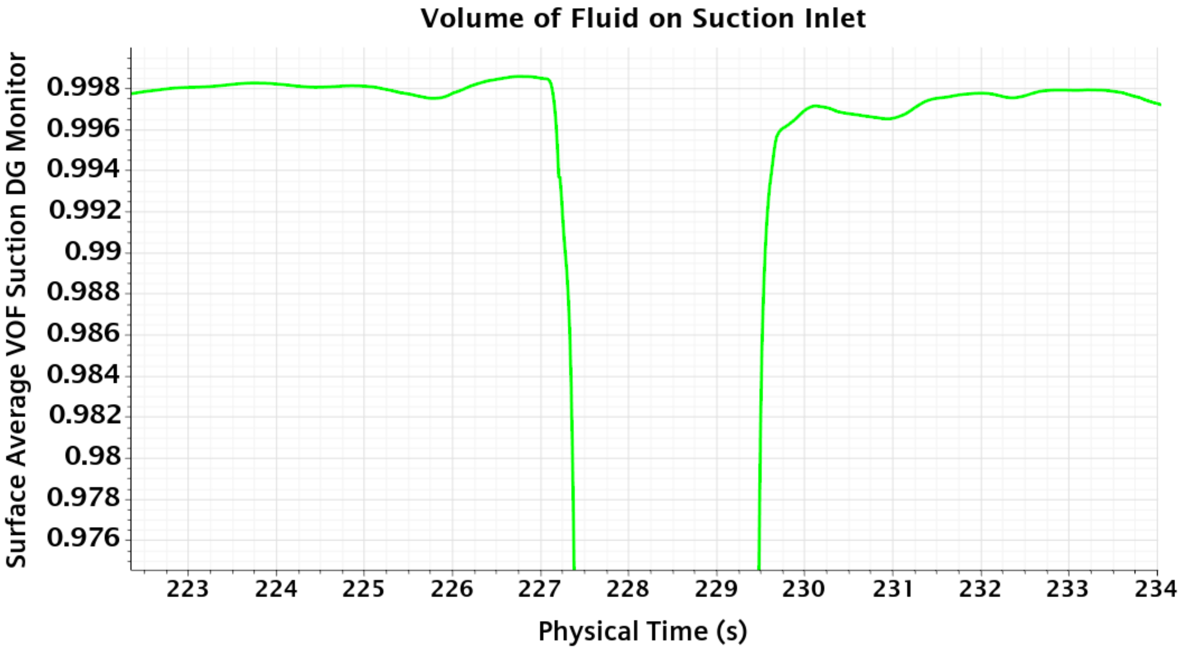

Figure B-6. Case 10; duration of event 2

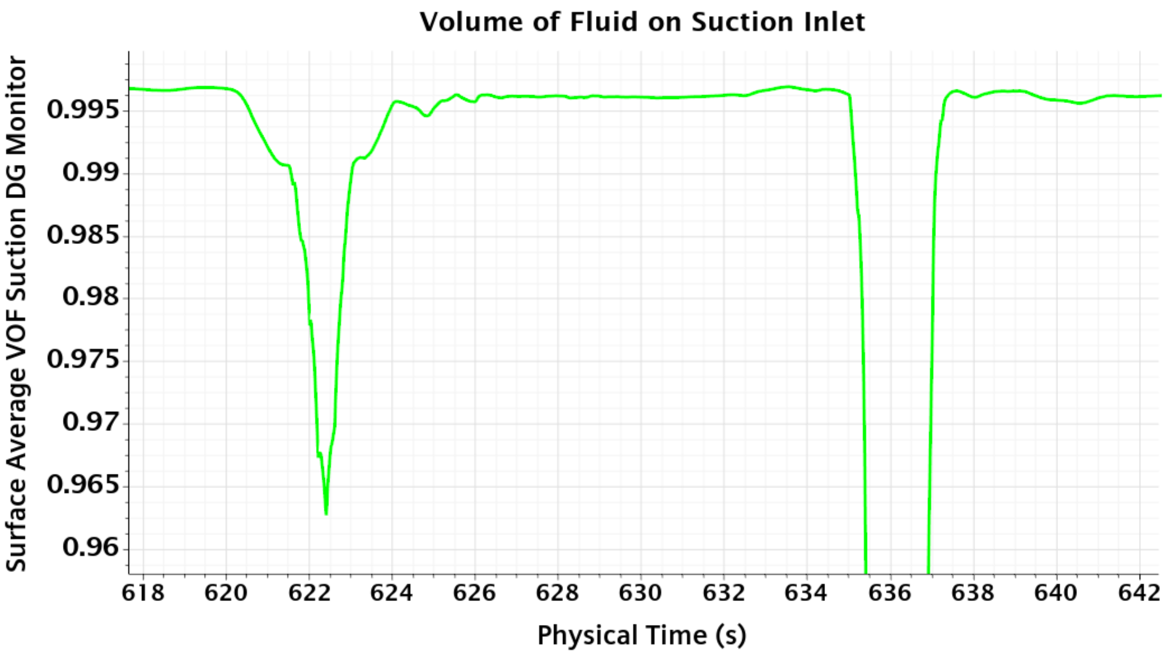

Figure B-7. Case 10; duration of events 3 and 4

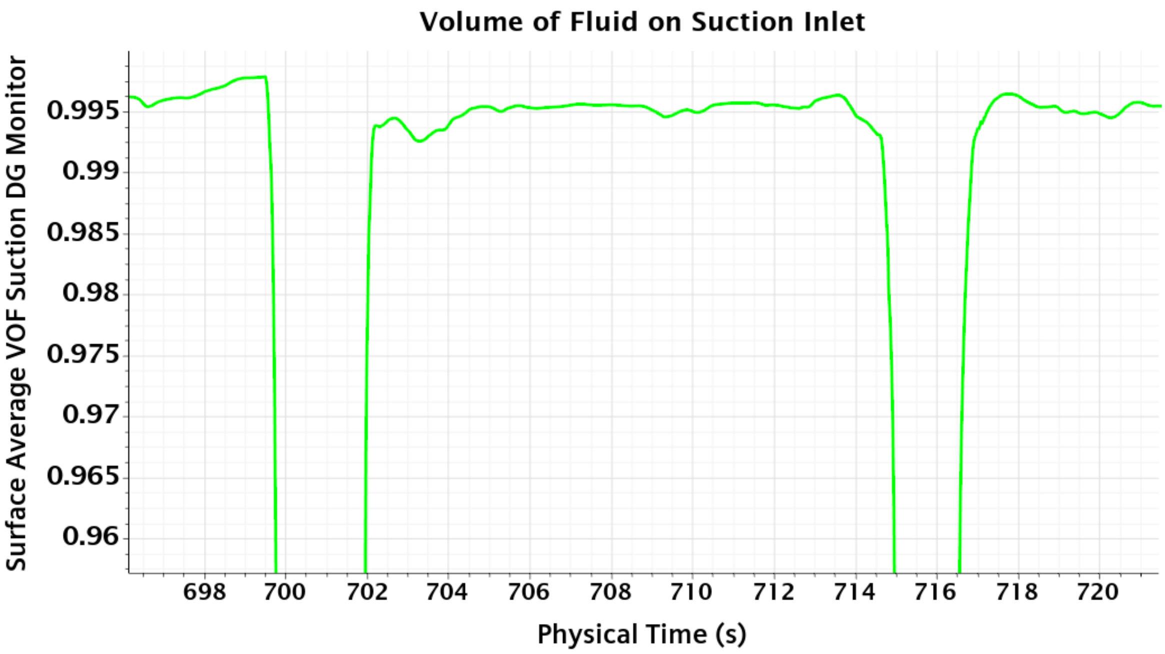

Figure B-8. Case 10; duration of events 5 and 6

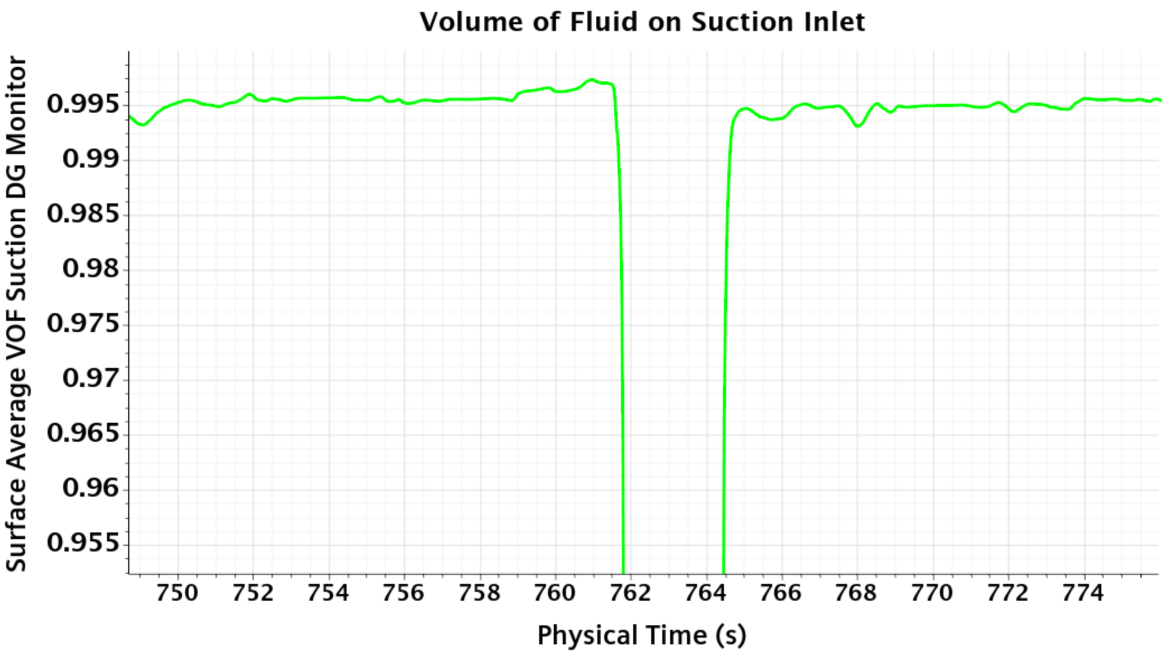

Figure B-9. Case 10; duration of event 7

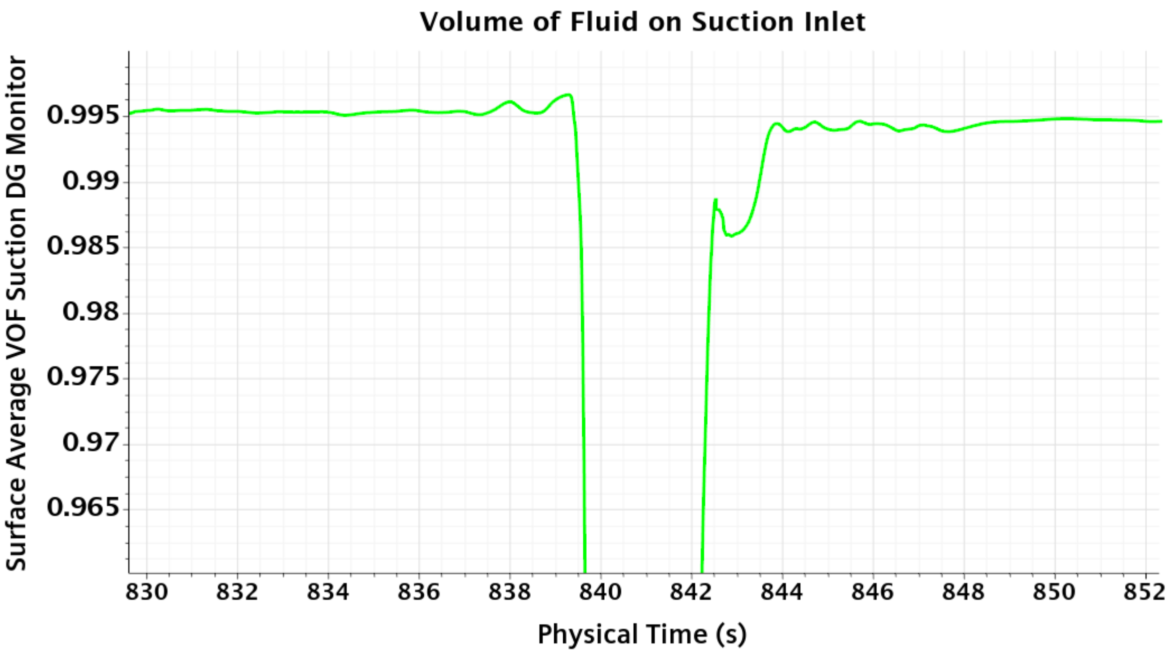

Figure B-10. Case 10; duration of event 8

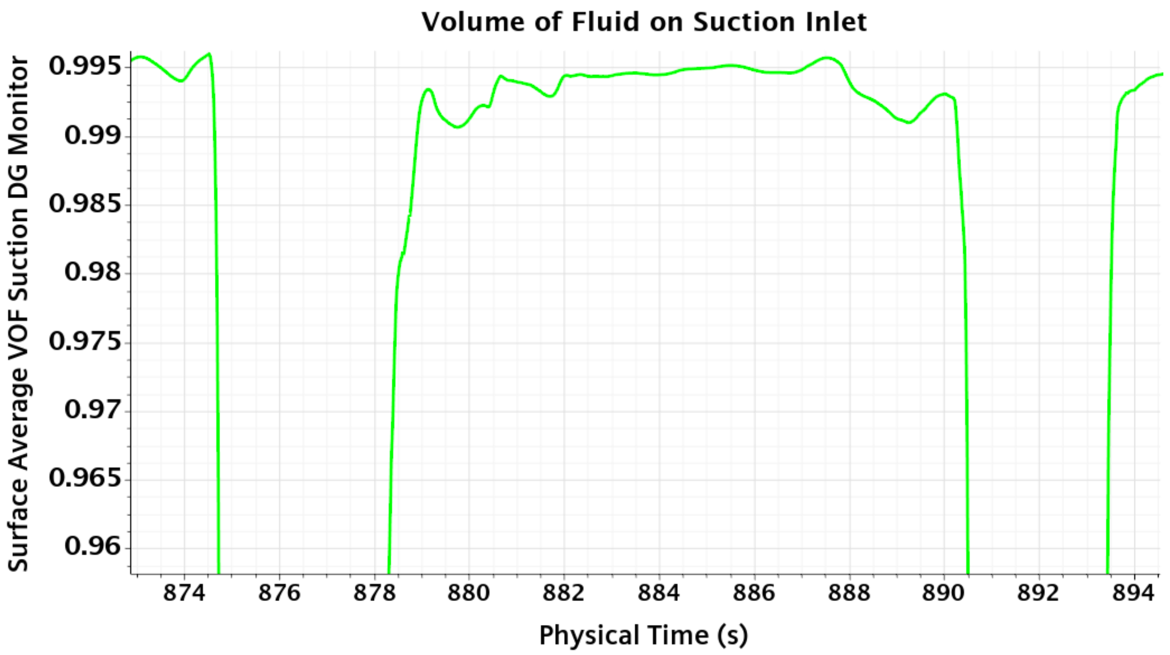

Figure B-11. Case 10; duration of events 9 and 10

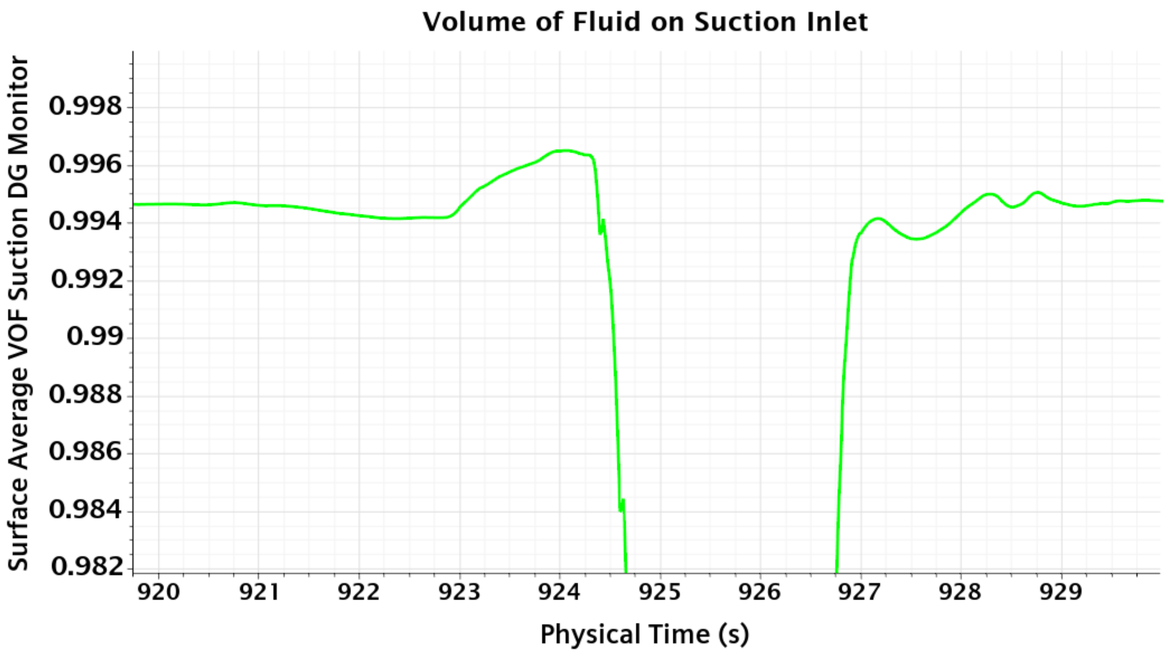

Figure B-12. Case 10; duration of event 11

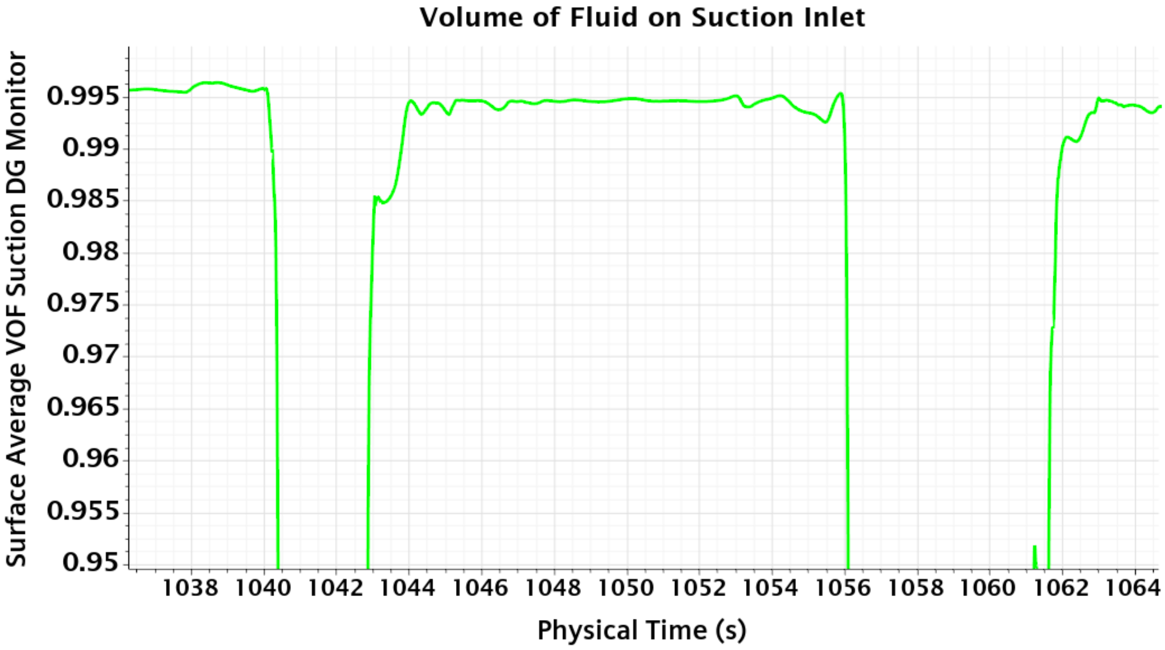

Figure B-13. Case 10; duration of event 12 and 13

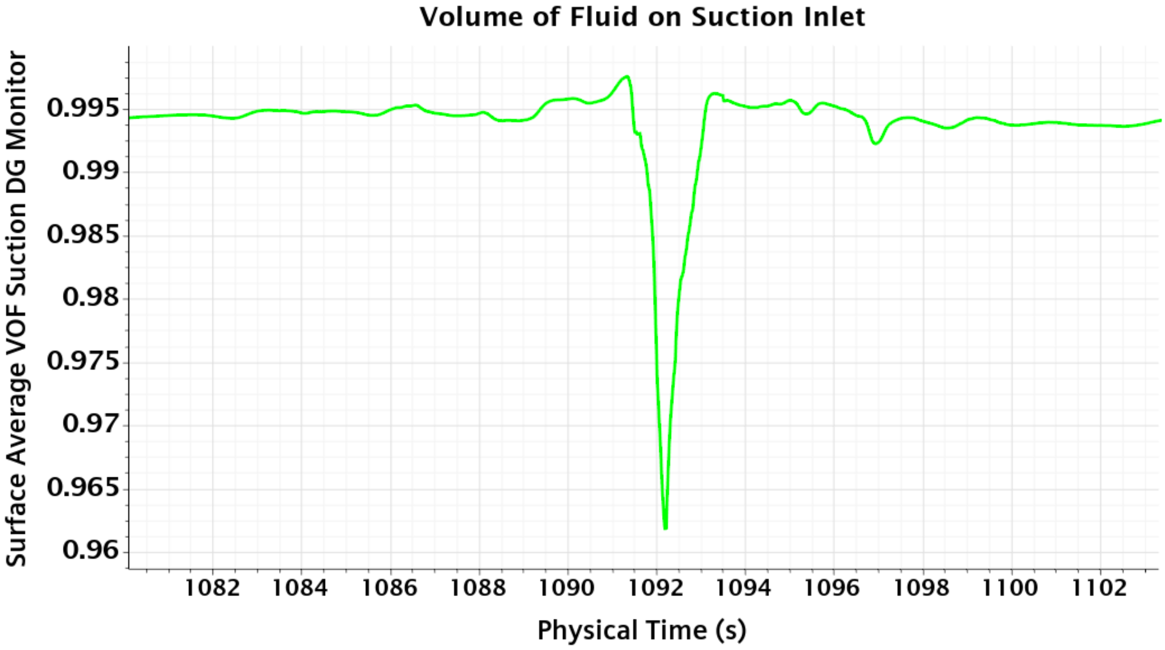

Figure B-14. Case 10; duration of event 14

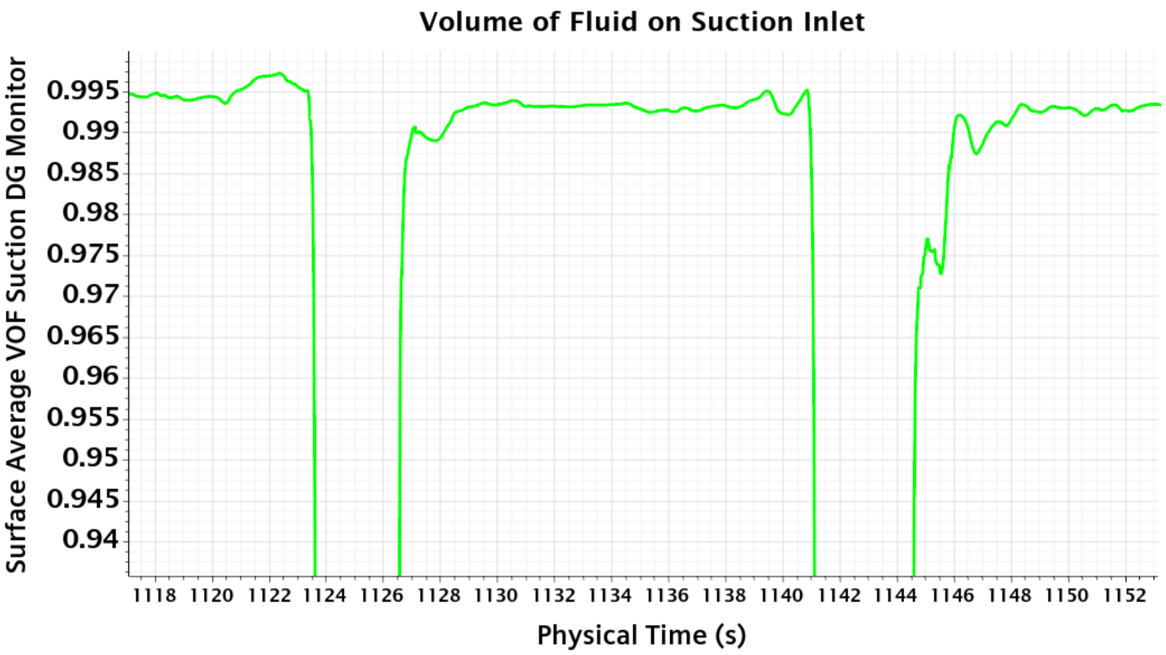

Figure B-15. Case 10; duration of events 15 and 16

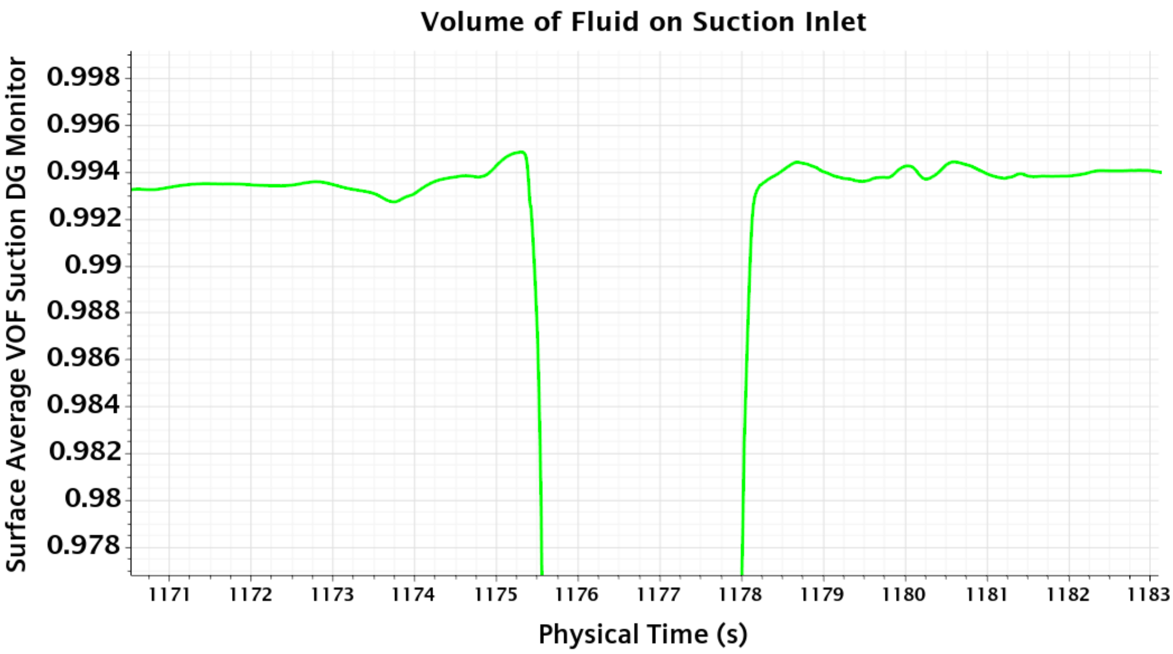

Figure B-16. Case 10; duration of event 17

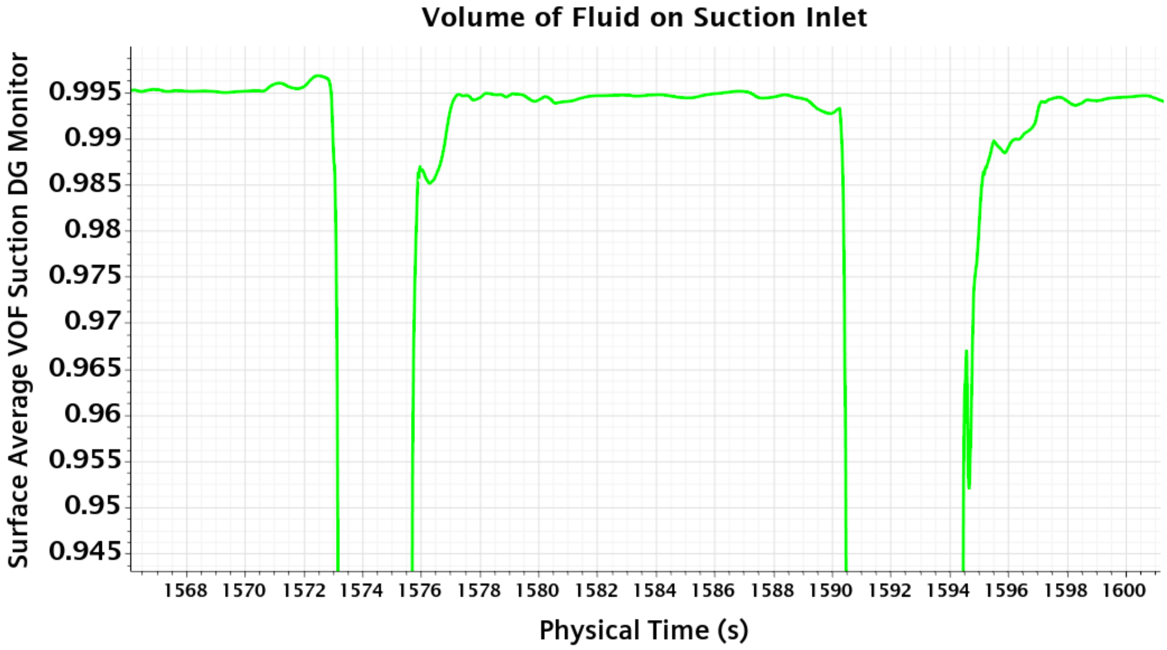

Figure B-17. Case 10; duration of events 18 and 19

B.2 Case 11

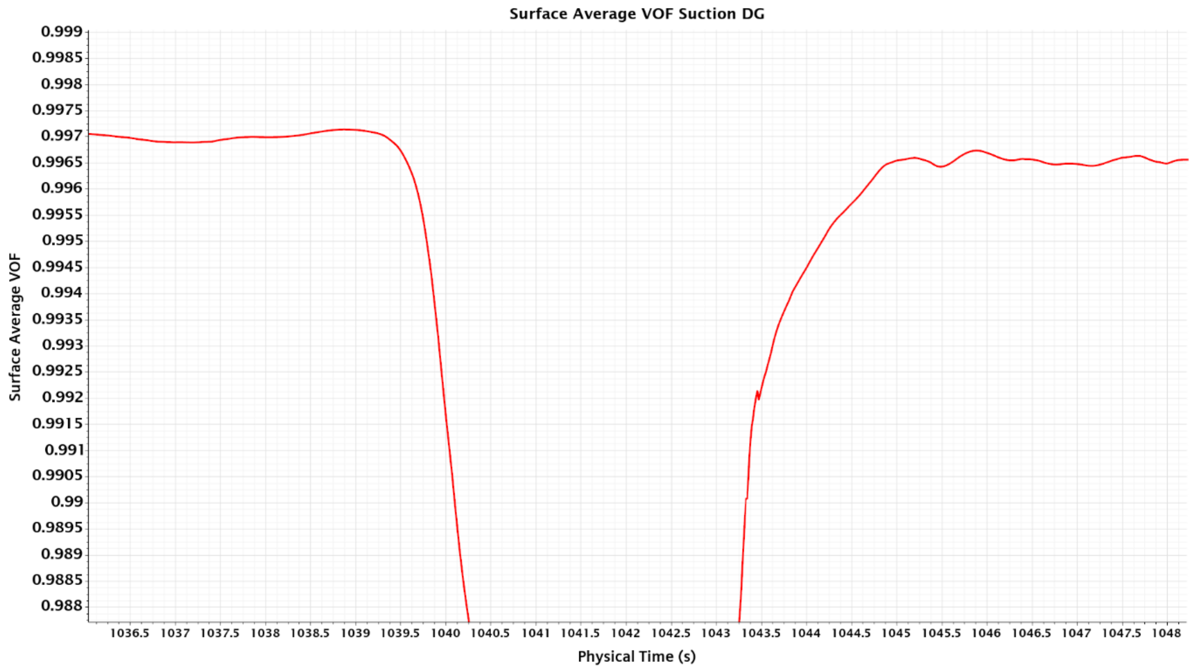

Figure B-18. Case 11; duration of event 1

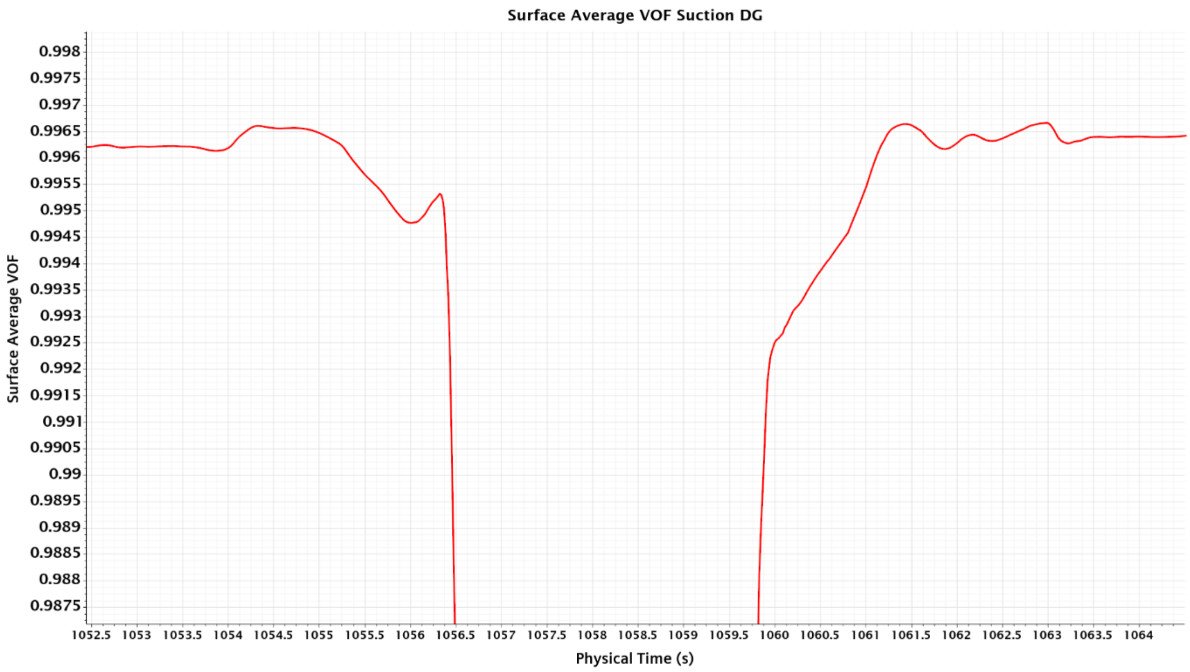

Figure B-19. Case 11; duration of event 2

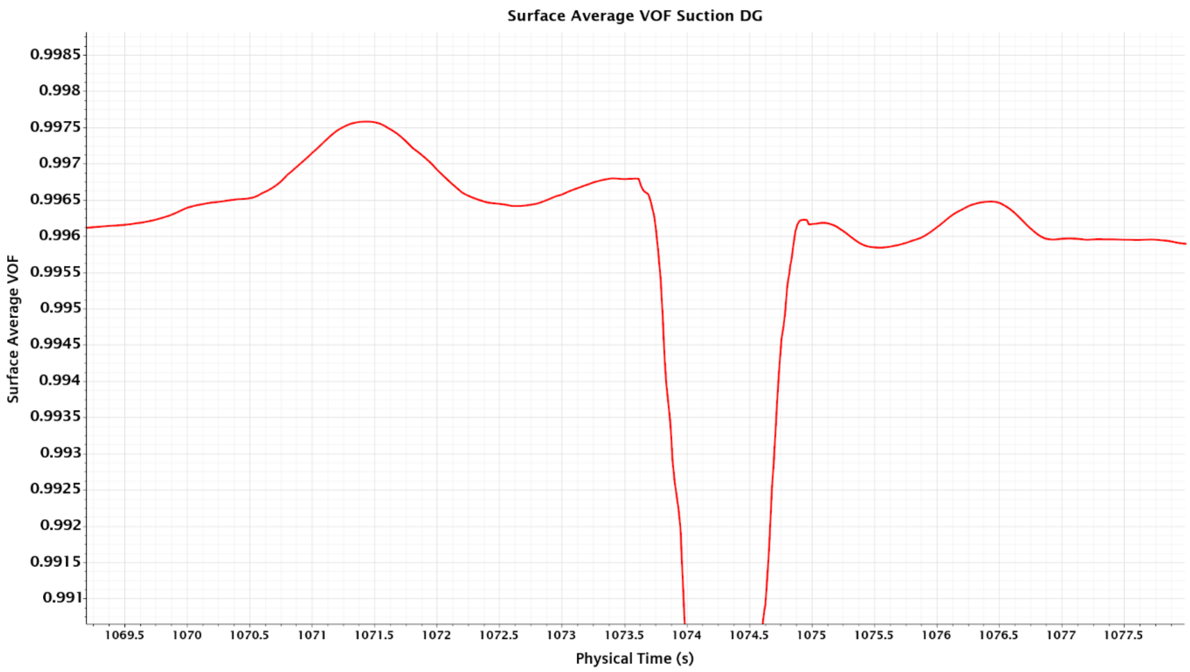

Figure B-20. Case 11; duration of event 3

Figure B-21. Case 11; duration of event 4

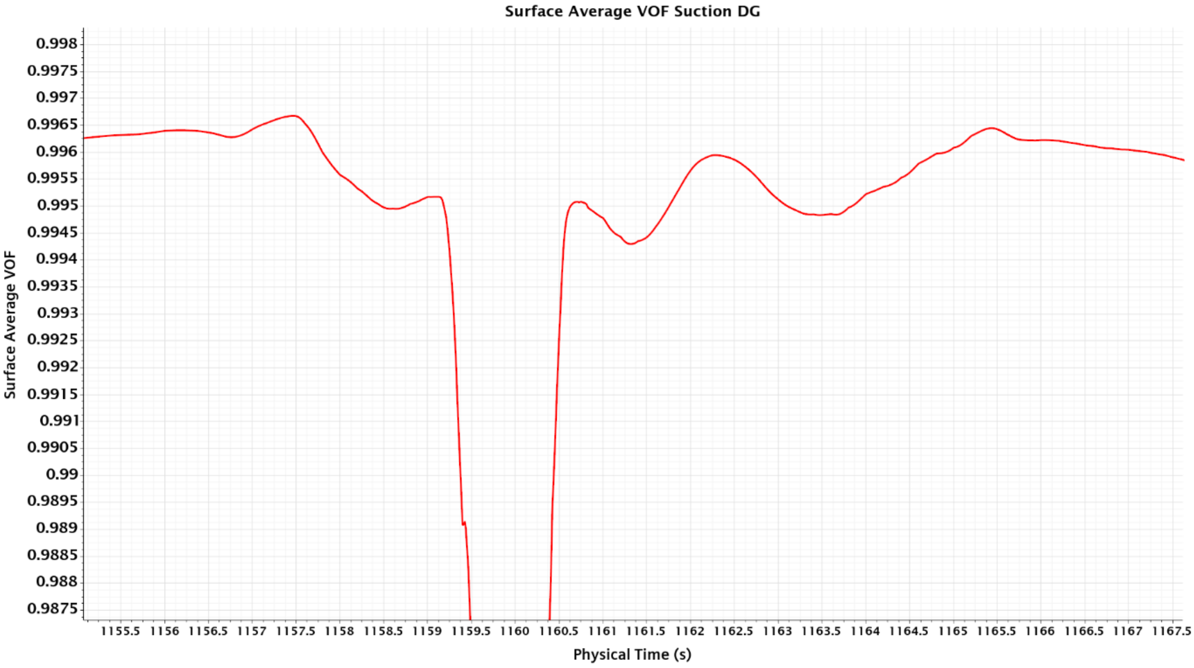

Figure B-22. Case 11; duration of event 5

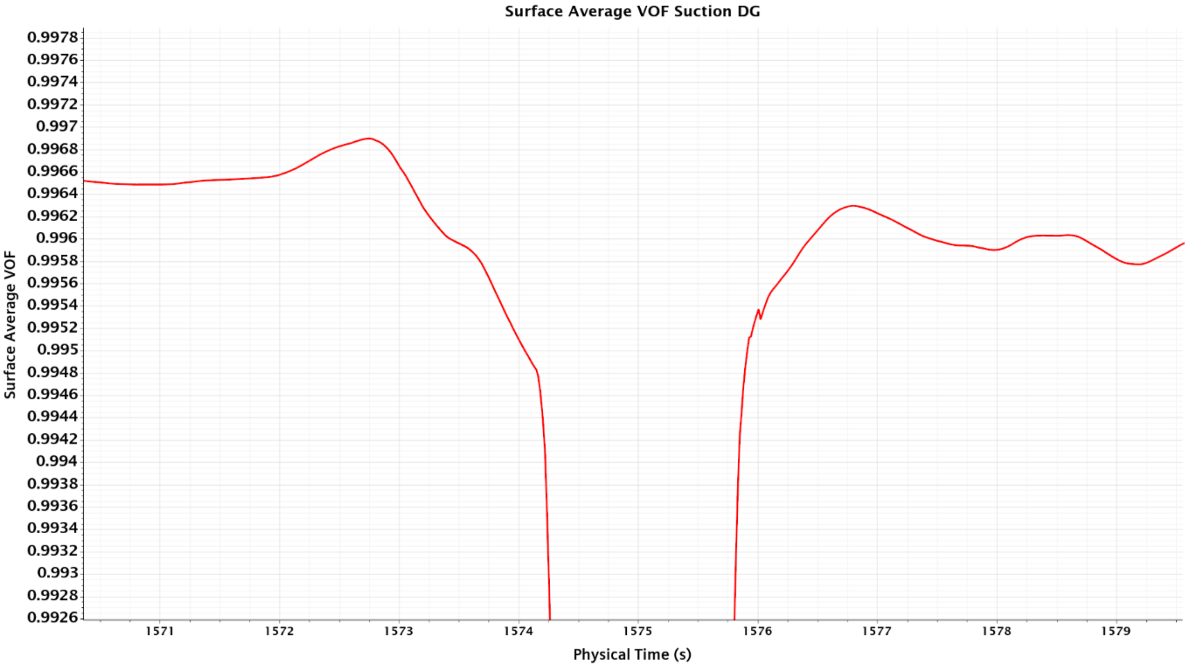

Figure B-23. Case 11; duration of event 6

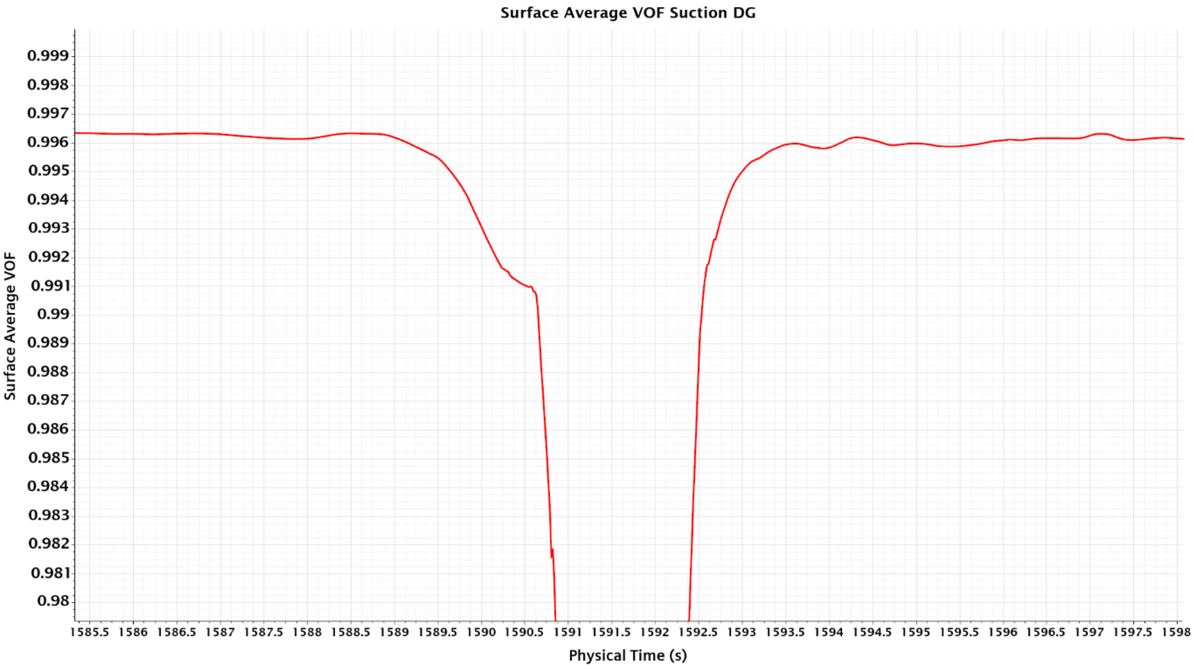

Figure B-24. Case 11; duration of event 7

B.3 Case 12

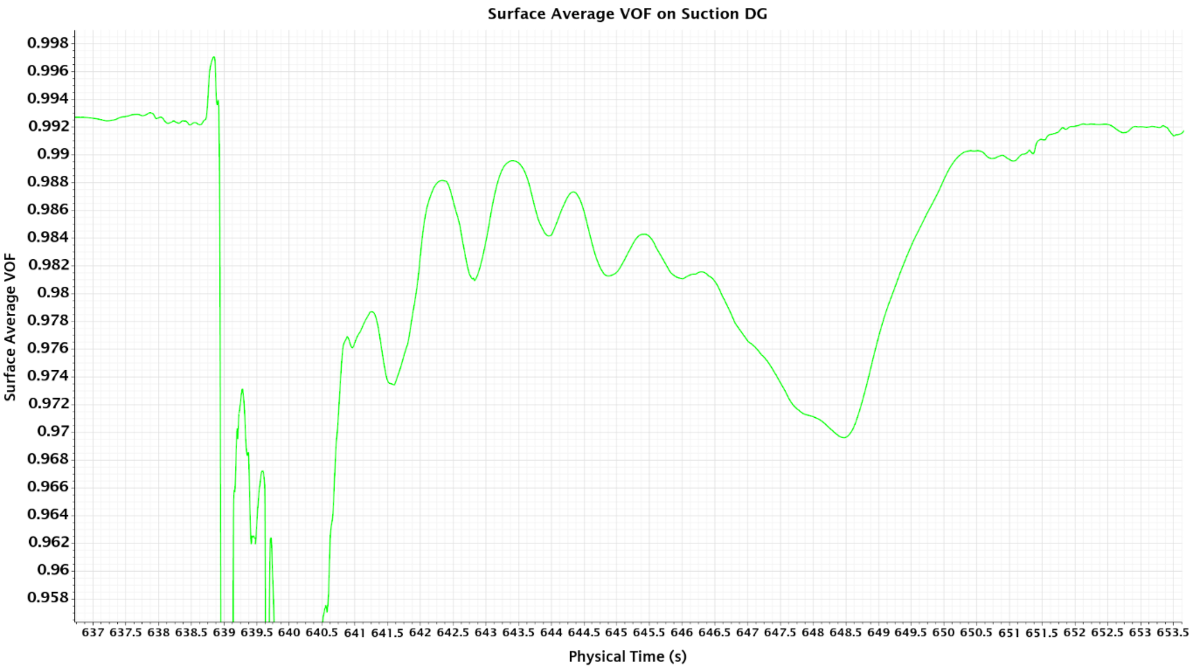

Figure B-25. Case 12; duration of event 1

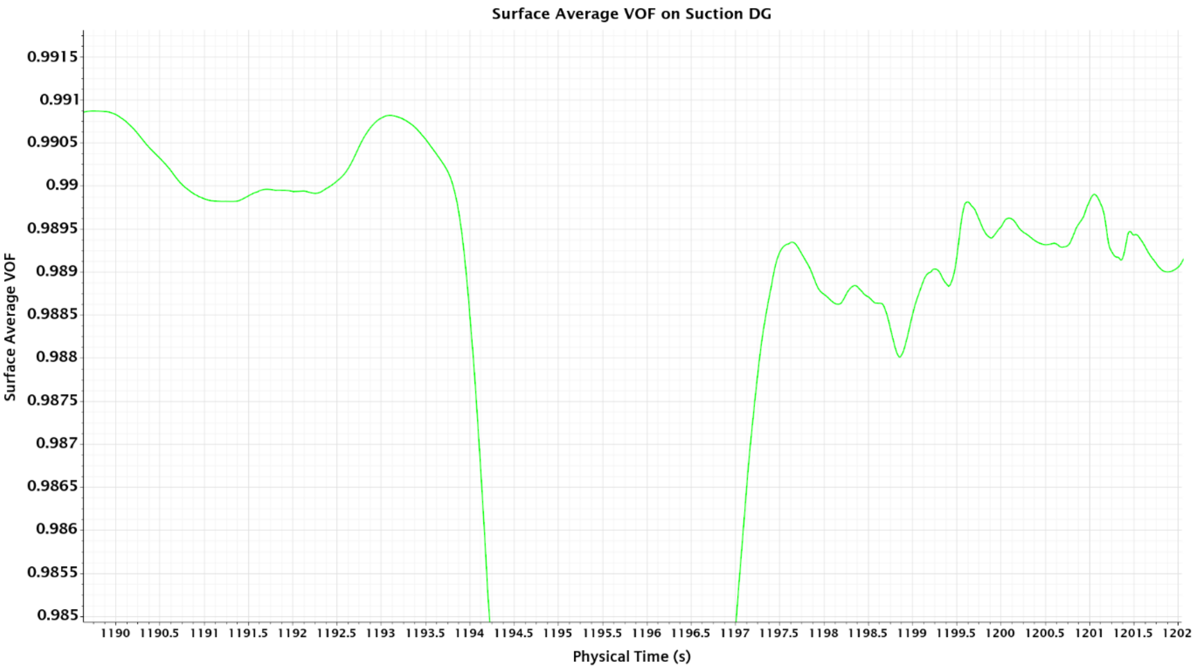

Figure B-26. Case 12; duration of event 2

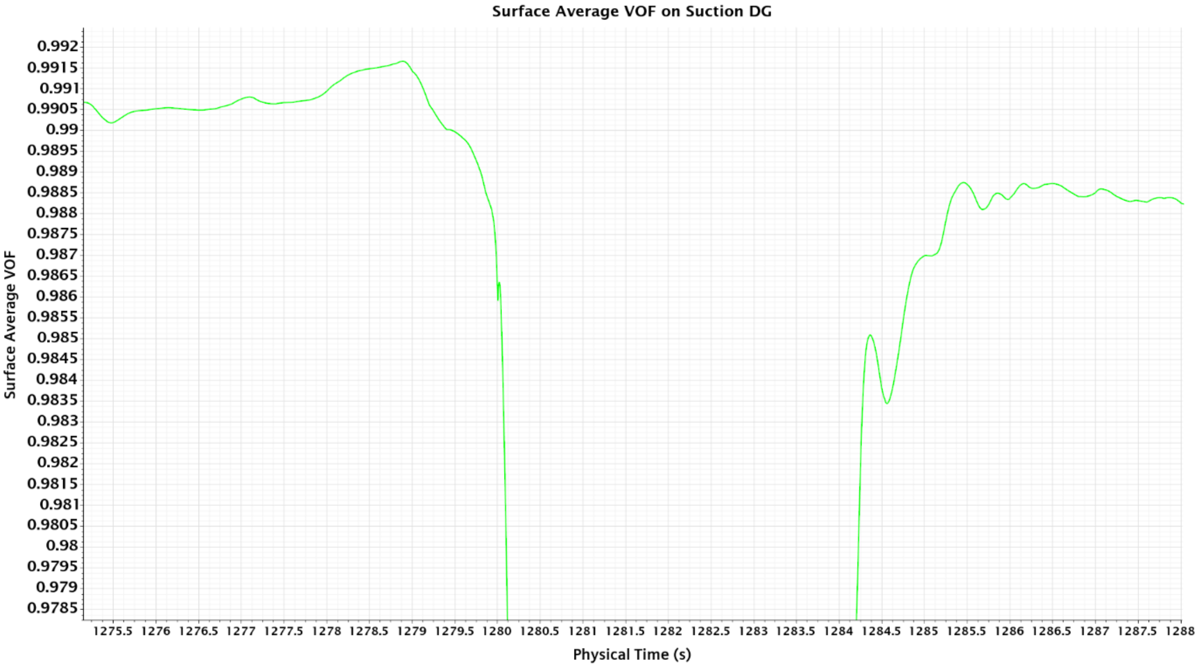

Figure B-27. Case 12; duration of event 3

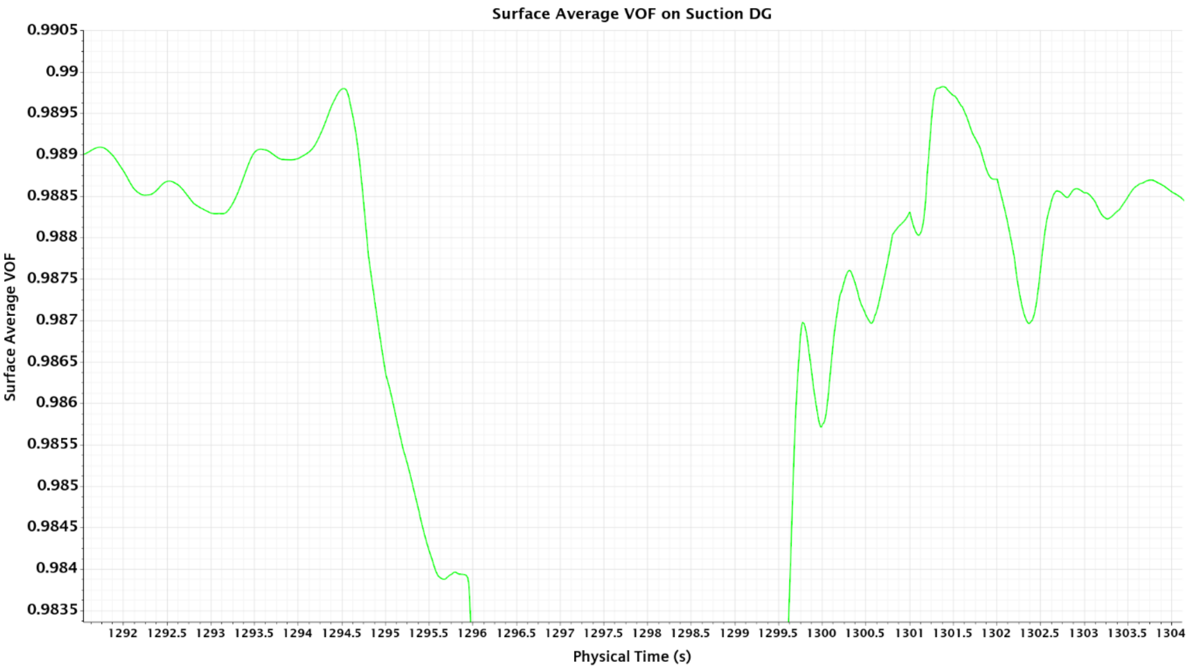

Figure B-28. Case 12; duration of event 4

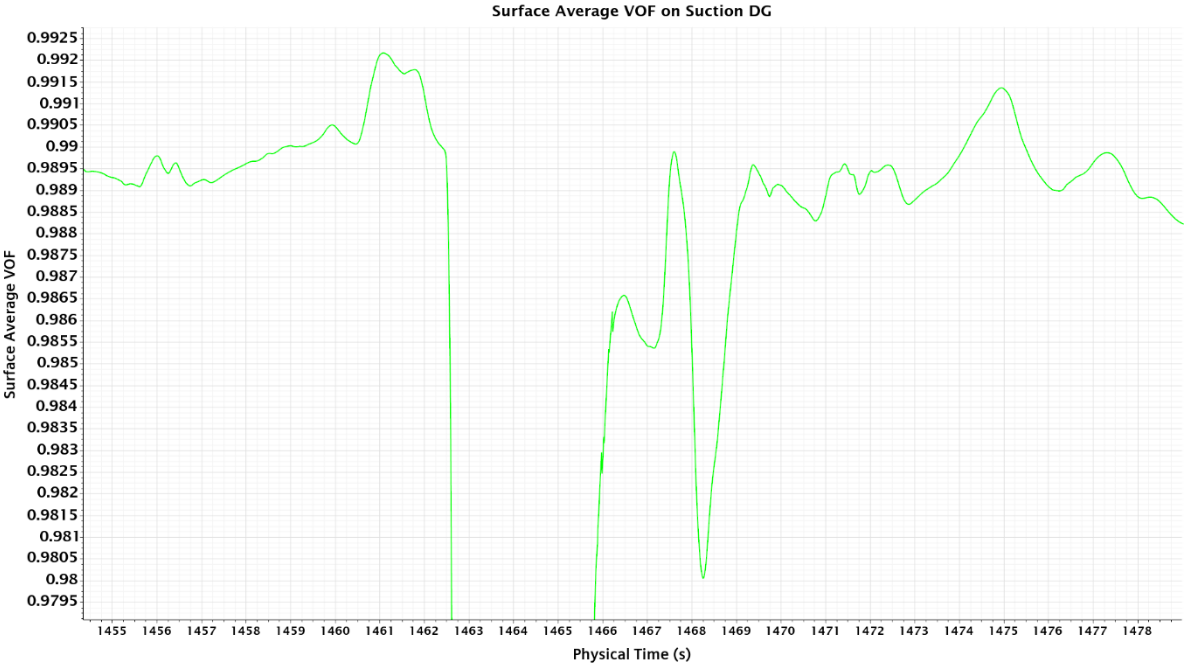

Figure B-29. Case 12; duration of event 5

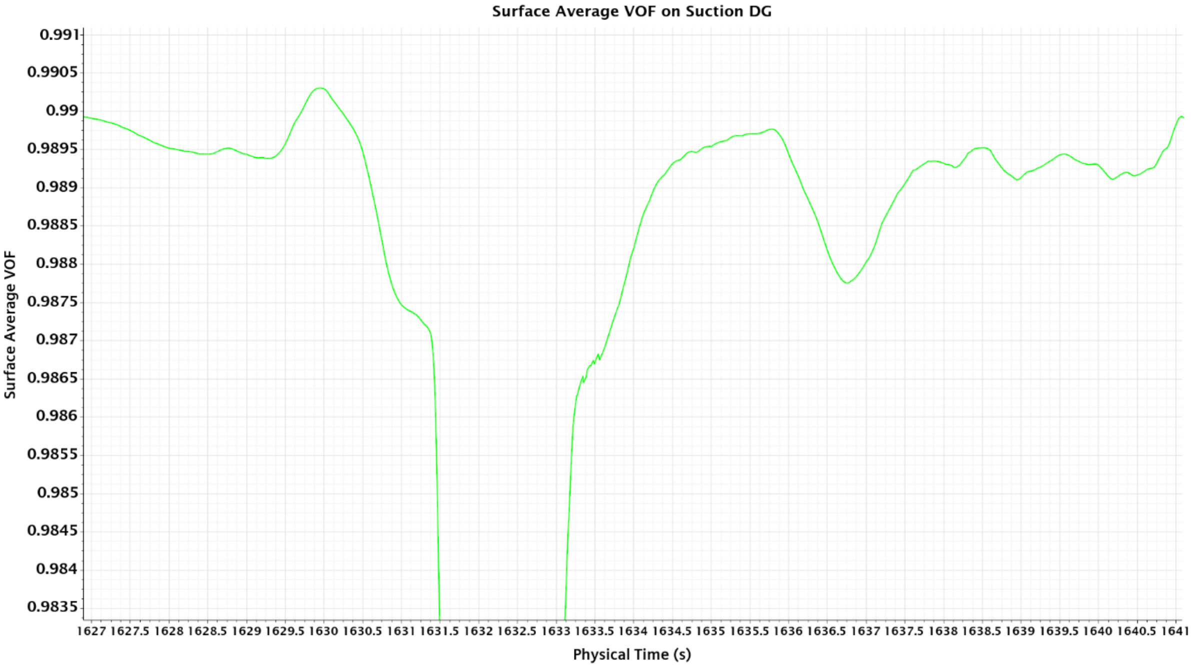

Figure B-30. Case 12; duration of event 6

B.4 Case 13

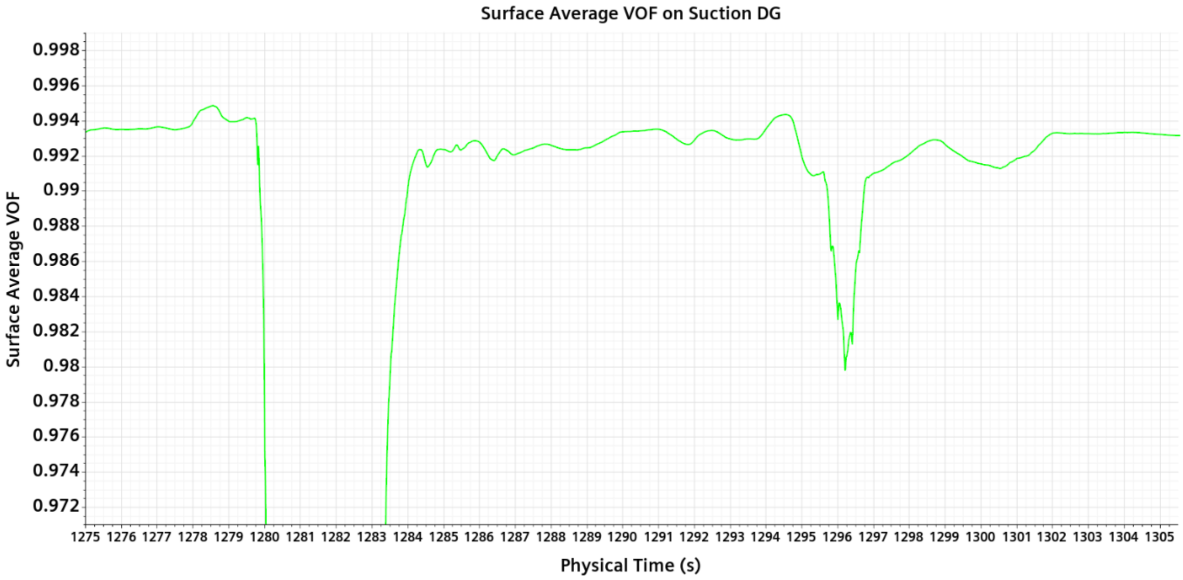

Figure B-31. Case 13; duration of events

B.5 Case 14

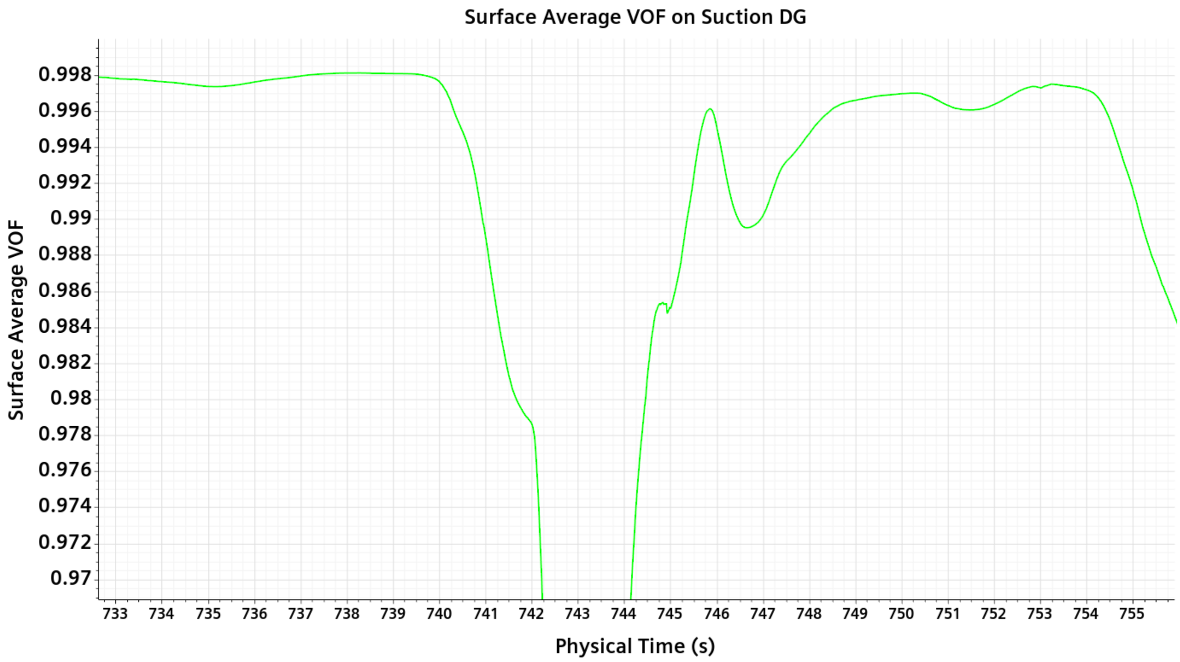

Figure B-32. Case 14; duration of event 1

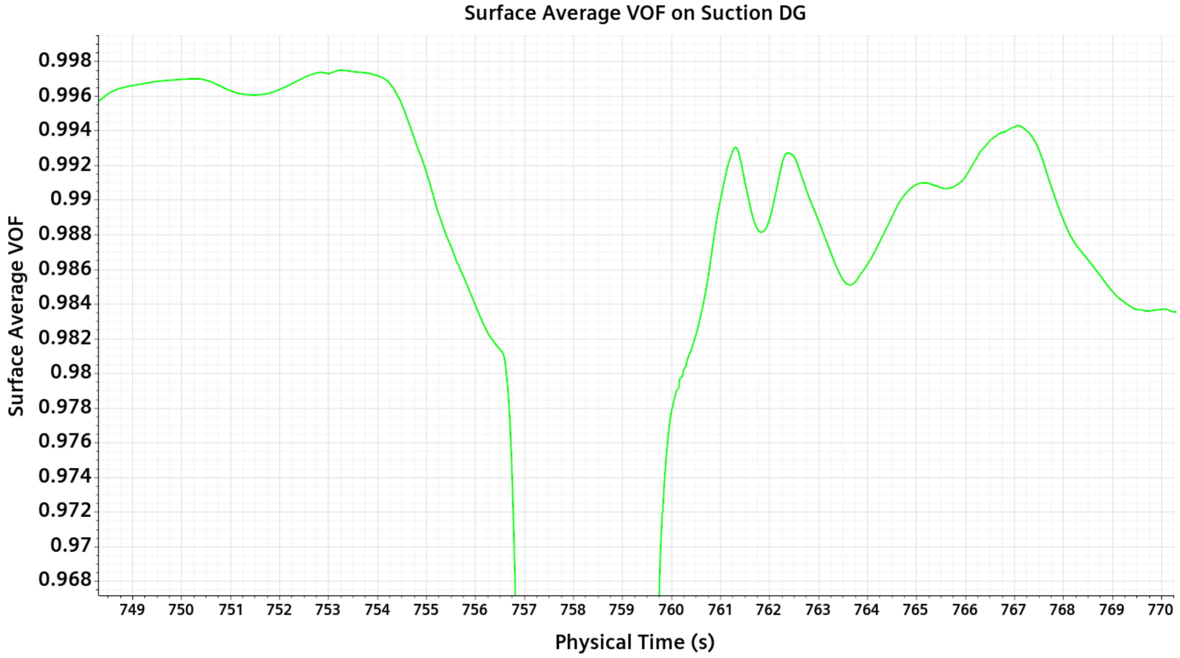

Figure B-33. Case 14; duration of event 2

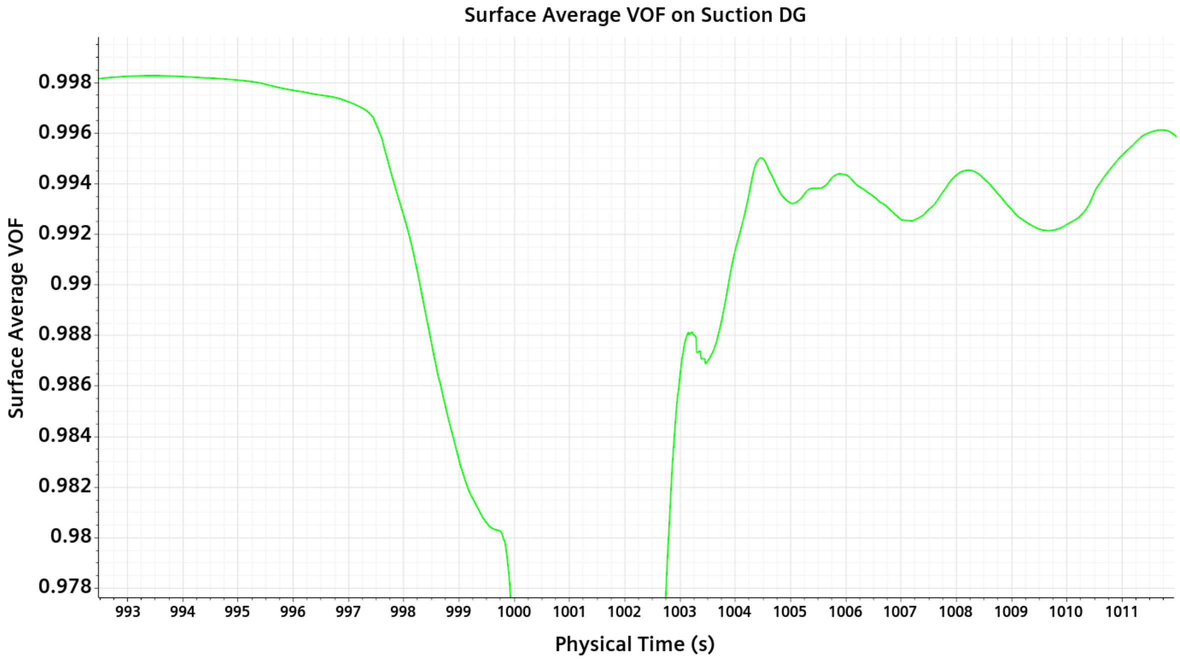

Figure B-34. Case 14; duration of event 3

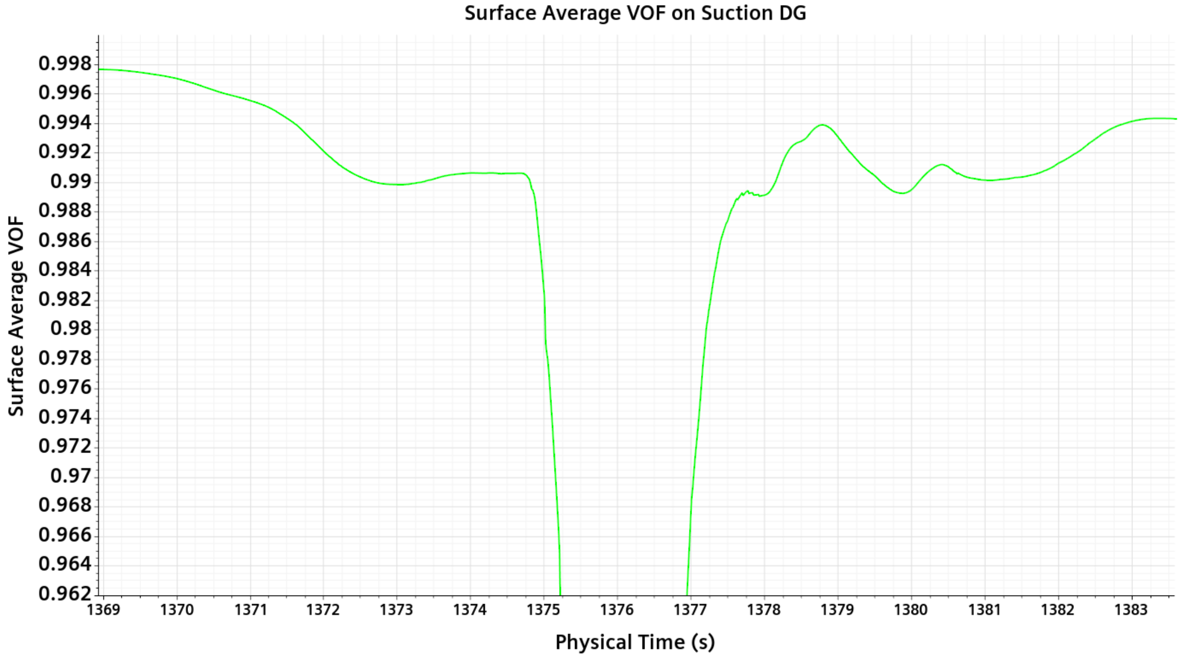

Figure B-35. Case 14; duration of event 4

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