

Steady-State and Transient Analysis of Explosion Protection Systems in Waste Heat Boiler Exhaust Ducting Using Aspen HYSYS

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Abstract: Reciprocating gas engines used in wastewater treatment and biogas facilities are commonly integrated with Waste Heat Boilers (WHBs) for energy recovery. During engine start-up and shutdown operations, combustible gas accumulation within exhaust ducting systems can create a risk of internal explosions or deflagration events. Proper design and placement of explosion protection devices, particularly rupture discs, are therefore critical to maintaining duct integrity and personnel safety.

This study presents a comprehensive steady-state and transient analysis of explosion protection systems installed in reciprocating engine exhaust ducting connected to a waste heat recovery system. Aspen HYSYS V14 was utilized to evaluate pressure distribution, temperature profiles, heat recovery performance, and transient pressure surge behavior under various operating scenarios involving biogas and natural gas firing. Three steady-state operating cases and three transient explosion scenarios were investigated. Dynamic simulations were conducted to validate rupture disc performance under deflagration conditions and to assess the effectiveness of single and dual rupture disc configurations.

The results demonstrate that while normal operating back pressures remain well below the engine trip limit of 6 kPag, transient surge pressures can exceed design thresholds when only a single rupture disc is installed. The introduction of a secondary rupture disc at the WHB inlet significantly reduced peak surge pressures from approximately 50.7 kPag to less than 38 kPag. The study confirms that a dual rupture disc arrangement provides superior explosion protection and improves overall exhaust system safety.

Keywords: Aspen HYSYS, Waste Heat Boiler, Explosion Protection, Rupture Disc, Dynamic Simulation, Exhaust Ducting, Deflagration Analysis, Biogas Engine.

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I. INTRODUCTION

The global wastewater treatment industry is increasingly utilizing biogas-fueled reciprocating gas engines to improve energy efficiency and reduce greenhouse gas emissions. The thermal energy available in engine exhaust gases is often recovered through Waste Heat Boilers (WHBs), thereby enhancing plant energy recovery and sustainability.

Despite the operational advantages of heat recovery systems, engine exhaust ducting networks remain vulnerable to combustible gas accumulation during start-up conditions. The presence of combustible mixtures within confined ducting may lead to deflagration events capable of generating rapid

pressure increases that exceed the mechanical design limits of the system. Such events can damage exhaust ducting, silencers, waste heat boilers, and associated process equipment.

AS 3814:2015 permits omission of purging requirements provided that adequate explosion relief devices are installed within the exhaust ducting system. Rupture discs represent one of the most applied passive explosion protection devices because they provide rapid pressure relief without requiring mechanical actuation.

The objective of this research is to evaluate the effectiveness of rupture disc placement strategies through steady-state and transient simulation modelling using Aspen HYSYS. Particular emphasis is placed on identifying optimal rupture disc locations and validating system behavior under abnormal operating scenarios.

II. LITERATURE REVIEW

Explosion protection in industrial combustion systems is governed by standards such as AS 3814, AS 1375, API 520, API 521, NFPA 68, ISO 4126, and ISO 6184. These standards provide methodologies for explosion vent sizing, pressure relief device selection and protection of process equipment exposed to rapid pressure rise conditions.

Previous studies have shown that conventional pressure relief valves are often unsuitable for explosion venting applications due to their response time limitations. Rupture discs provide instantaneous opening characteristics and larger effective vent areas, making them effective for deflagration protection.

Dynamic process simulation has emerged as a powerful tool for evaluating transient phenomena in industrial systems. Aspen HYSYS enables engineers to model pressure wave propagation, rupture disc activation, flow redistribution and equipment interactions under abnormal operating scenarios. Such simulations provide significant advantages compared to

traditional empirical calculations by allowing detailed evaluation of system-wide transient responses.

III. OBJECTIVE

The primary objectives of this research are:

- To evaluate steady-state pressure and temperature profiles within a reciprocating engine exhaust system.
- To analyze transient pressure surge behavior caused by internal deflagration events.
- To validate rupture disc sizing and placement based on simulation results.
- To compare performance between single and dual rupture disc configurations.
- To develop recommendations for explosion protection in long exhaust duct systems.

IV. METHODOLOGY

➤ System Description

The study investigated a reciprocating gas engine exhaust system connected to a Waste Heat Boiler and vertical exhaust stack. The total exhaust duct length was approximately 22 m. Existing protection consisted of a DN400 rupture disc positioned near the silencer inlet. An additional DN300 rupture disc was proposed at the WHB inlet.

Table 1 Operating and Design Conditions of WHB Exhaust System

Parameter	Values
Operating Temperature	390-450°C
Operating Pressure	2-3 kPag
Engine Trip Pressure	>6 kPag
Design Temperature	460°C

➤ Simulation Software

Aspen HYSYS Version 14 was utilized for both steady-state and dynamic simulations. The Peng-Robinson thermodynamic package was selected to model exhaust gas behavior containing CO₂, H₂O, N₂, O₂, CO, NO_x and SO₂ components.

➤ Steady-State Simulation Modelling

Three operating scenarios were considered as per Table-2 below:

Table 2 Operating Simulation Cases

Case	Fuel Type	Engine Load
Case 1	Biogas	75%
Case 2	Biogas	100%
Case 3	Natural Gas	100%

The simulation objectives included:

- Exhaust back-pressure validation.
- Pressure distribution analysis.
- Temperature profile analysis.
- Heat recovery evaluation across the WHB.
- Verification of operational compliance with engine requirements.

➤ Dynamic Simulation Modelling

Dynamic simulations were performed to evaluate system response during internal explosion scenarios.

• Design Case 1:

Single rupture disc configuration:

- ✓ RD-1 at silencer inlet.
- ✓ Set pressure = 40 kPag.

- **Design Case 2:**
Dual rupture disc configuration:

- ✓ RD-1 at silencer inlet.
- ✓ Set pressure = 40 kPag.
- ✓ RD-2 at WHB inlet.
- ✓ Set pressure = 30 kPag.

- **Sensitivity Case 3:**

- ✓ Natural gas operation.
- ✓ Single rupture disc arrangement.
- ✓ RD-1 set pressure = 40 kPag.

The transient event was initiated by applying a pressure surge representative of an internal deflagration while the WHB bypass valve remained closed. Pressure propagation and rupture disc activation were monitored throughout the exhaust system.

V. RESULTS AND DISCUSSION

➤ Steady-State Performance

The steady state performance results are summarized below for various operating scenarios.

- **Case 1: Biogas at 75% Load**

Table 3 Case 1 Biogas @ 75% Load

Parameter	Values
Exhaust Flow	6146 kg/hr
Exhaust Temperature	430°C
Exhaust Pressure	2.2 kPag
WHB Heat Duty	414.6 kW
WHB Outlet Temperature	218.3°C

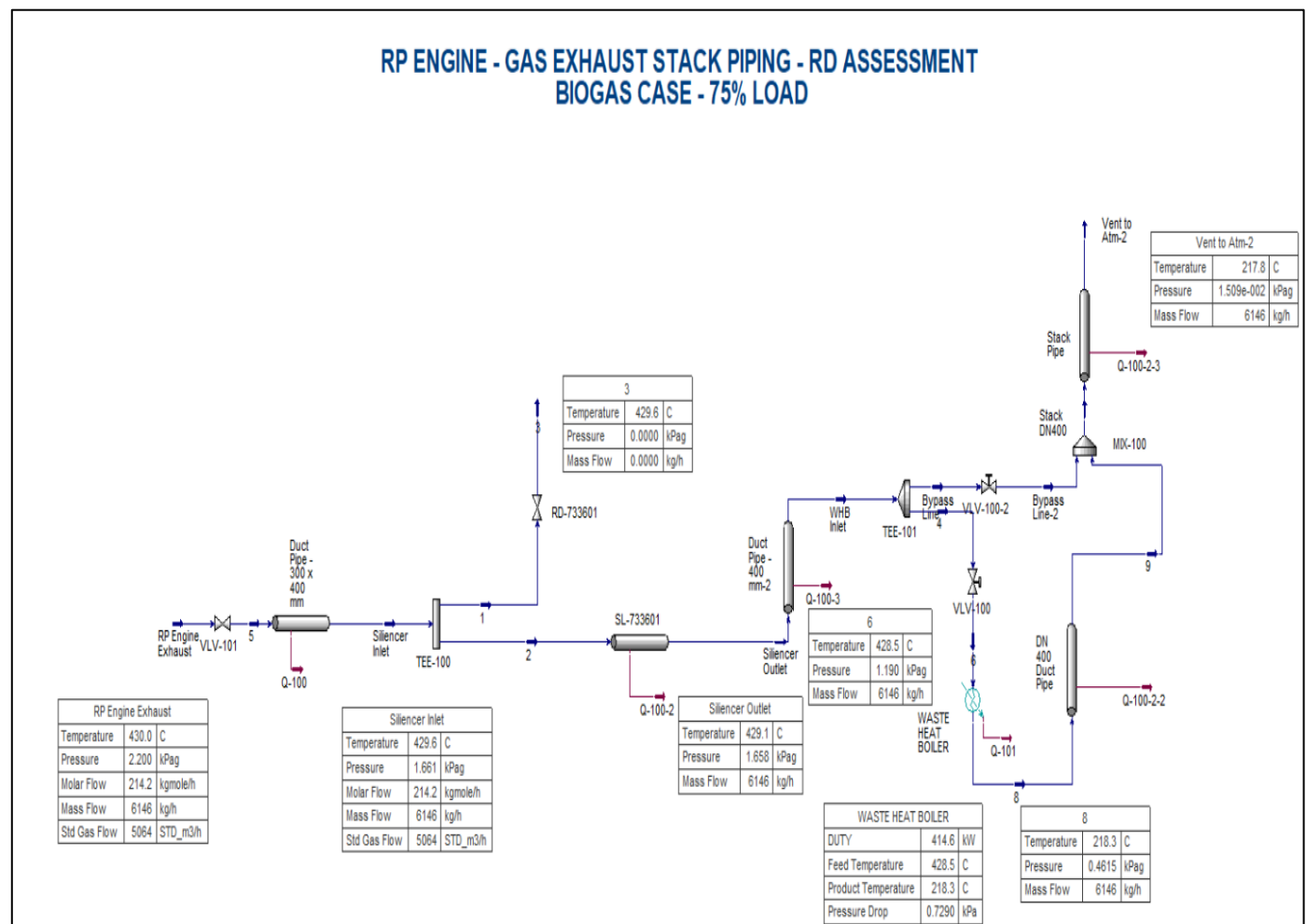


Fig 1 Case 1 Biogas @ 75% Load Simulation Results

Table 4 Case 2 Biogas @ 100% Load

Parameter	Values
Exhaust Flow	8096 kg/hr
Exhaust Temperature	410°C
Exhaust Pressure	3.5 kPag
WHB Heat Duty	482.5 kW
WHB Outlet Temperature	222.8°C

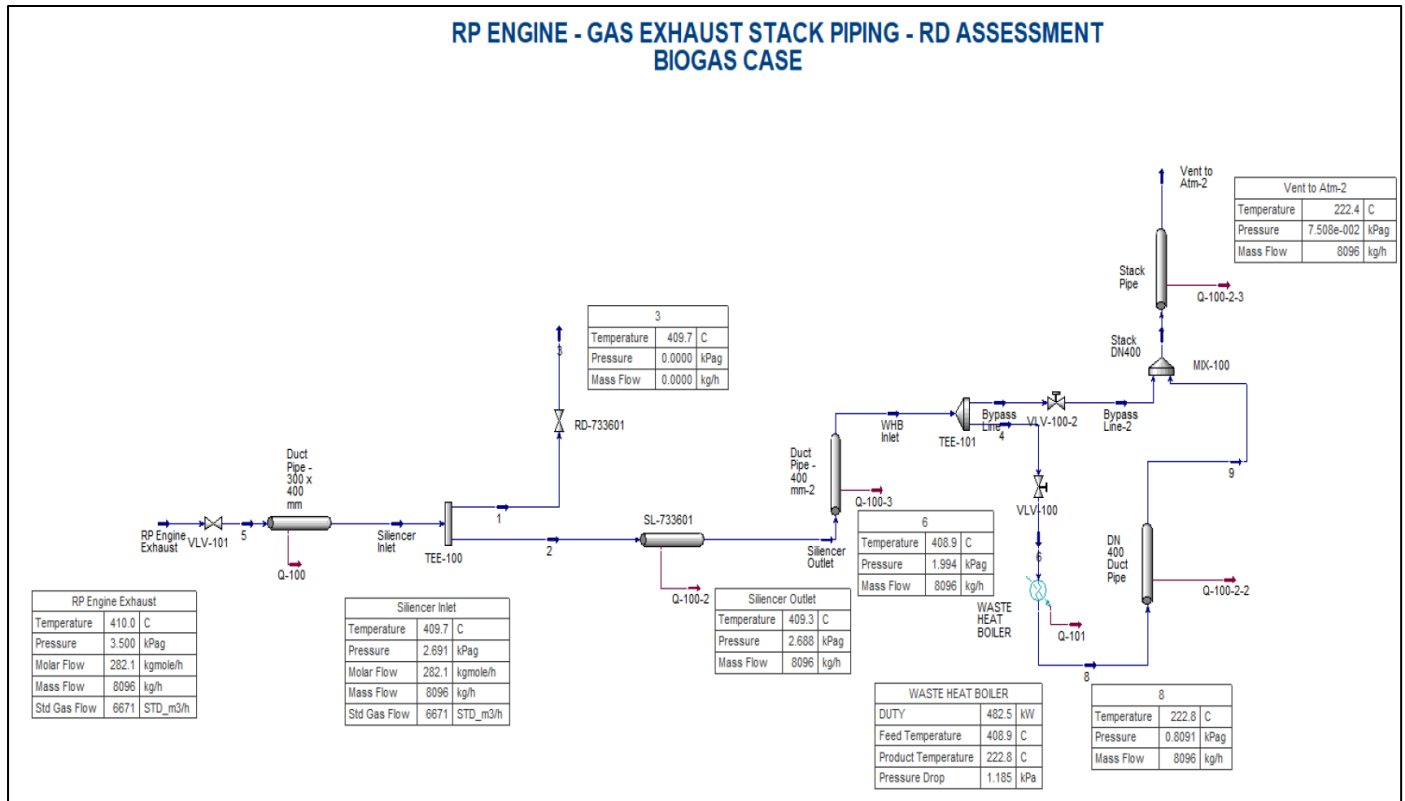


Fig 2 Case 2 Biogas @ 100% Load Simulation Results

Table 5 Case 3 Natural Gas @ 100% Load

Parameter	Values
Exhaust Flow	7352 kg/hr
Exhaust Temperature	390°C
Exhaust Pressure	2.9 kPag
WHB Heat Duty	399.2 kW
WHB Outlet Temperature	219.7°C

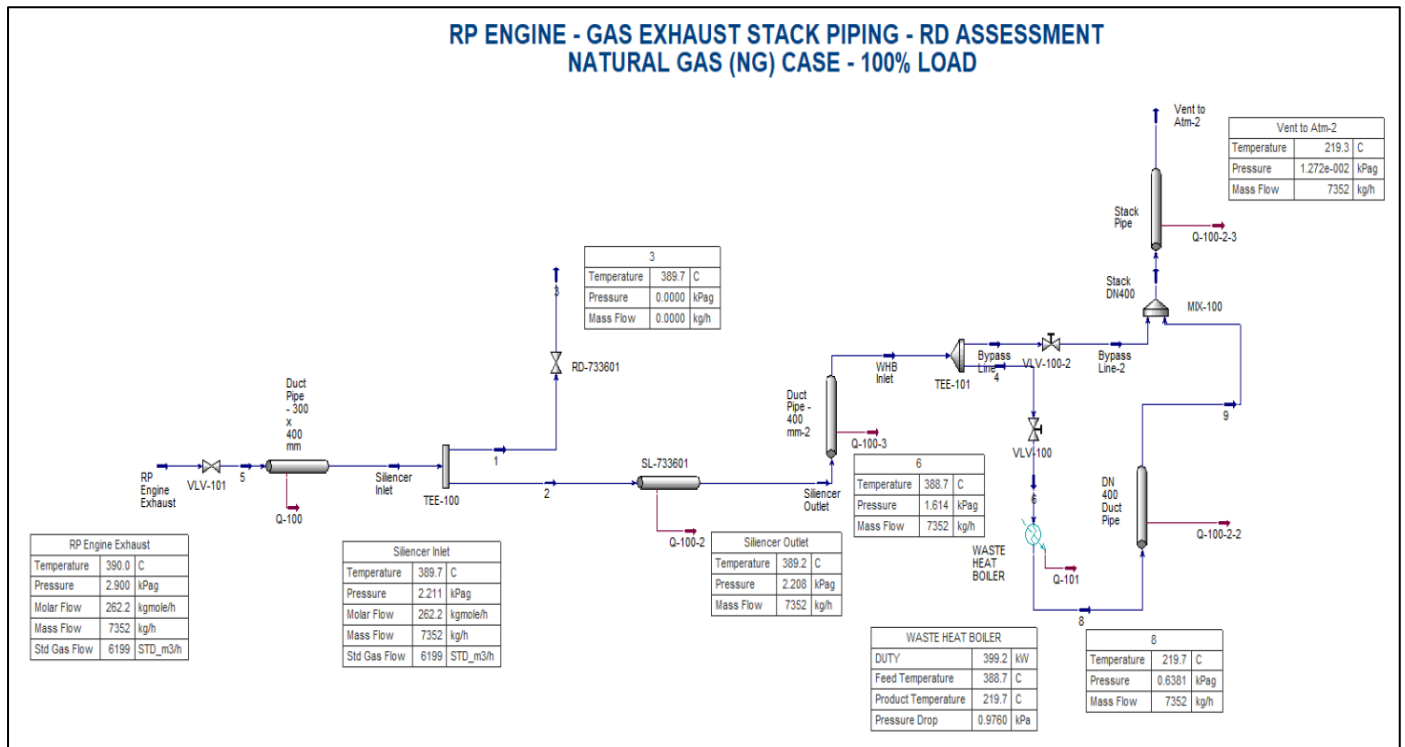


Fig 3 Case 3 Natural Gas @ 100% Load Simulation Results

➤ Steady-State Findings

All operating cases demonstrated acceptable system performance. Maximum exhaust back pressure remained below 3.5 kPag, significantly lower than the engine trip limit of 6 kPag. The WHB recovered between 399 and 483 kW of thermal energy, confirming the effectiveness of the heat recovery system.

➤ Transient Analysis Results

• Single Rupture Disc Configuration

For biogas operation under Design Case 1, pressure peaked at approximately 50.6 kPag before rupture disc activation. This value slightly exceeded the duct design pressure of 50 kPag.

• Dual Rupture Disc Configuration

When a second rupture disc was installed at the WHB inlet, maximum surge pressure decreased to approximately 37.8 kPag. The WHB inlet rupture disc activated first at 30 kPag, effectively dissipating the pressure wave and preventing excessive pressure accumulation.

• Natural Gas Sensitivity Analysis

For natural gas operation with a single rupture disc, peak pressure reached approximately 48 kPag, remaining marginally below the duct design pressure limit.

Refer below figures from 4 to 6 for dynamic simulation results for all simulated cases.

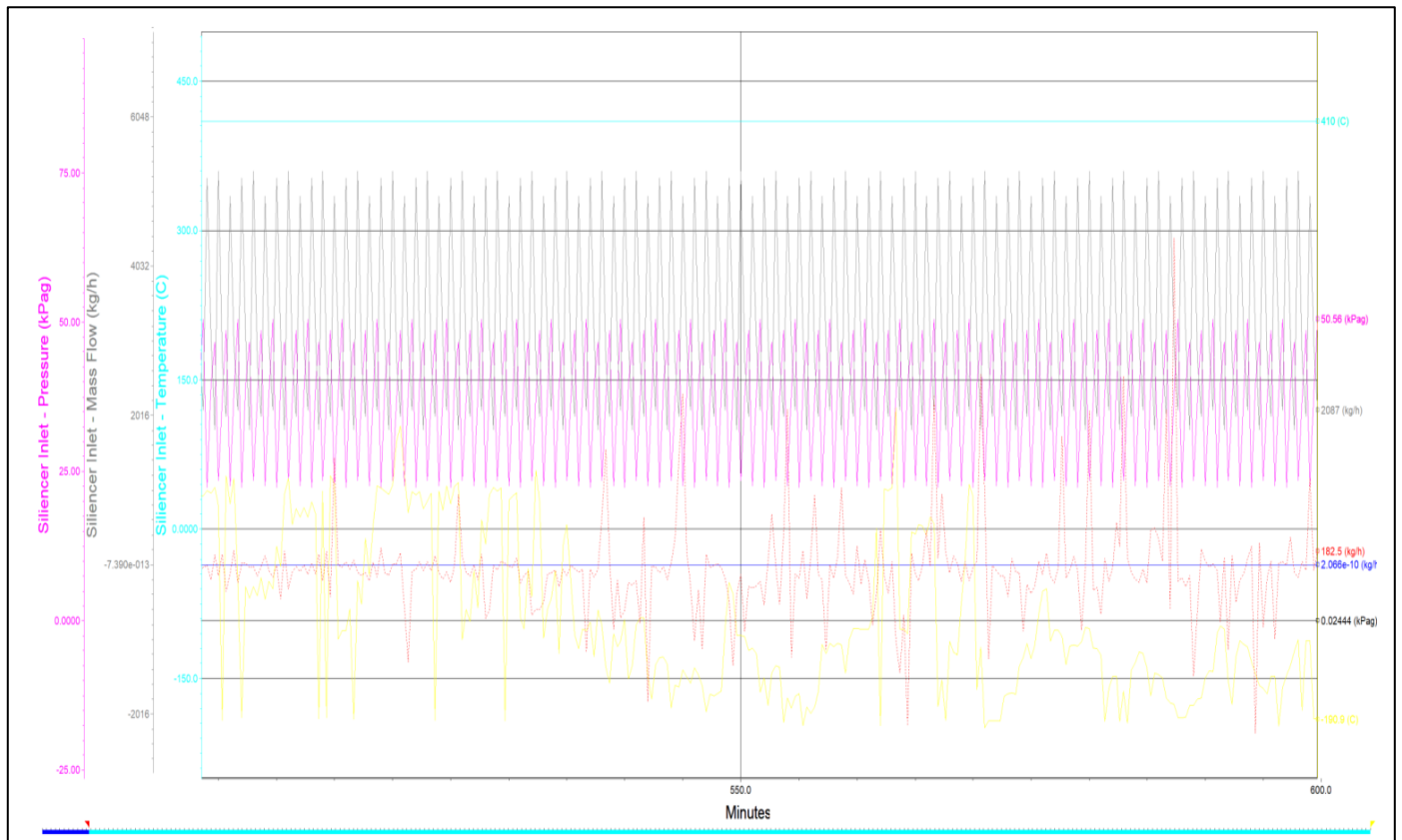


Fig 4 Case 1 Biogas @ 750% Load Dynamic Simulation Results



Fig 5 Case 2 Biogas @ 100% Load Dynamic Simulation Results

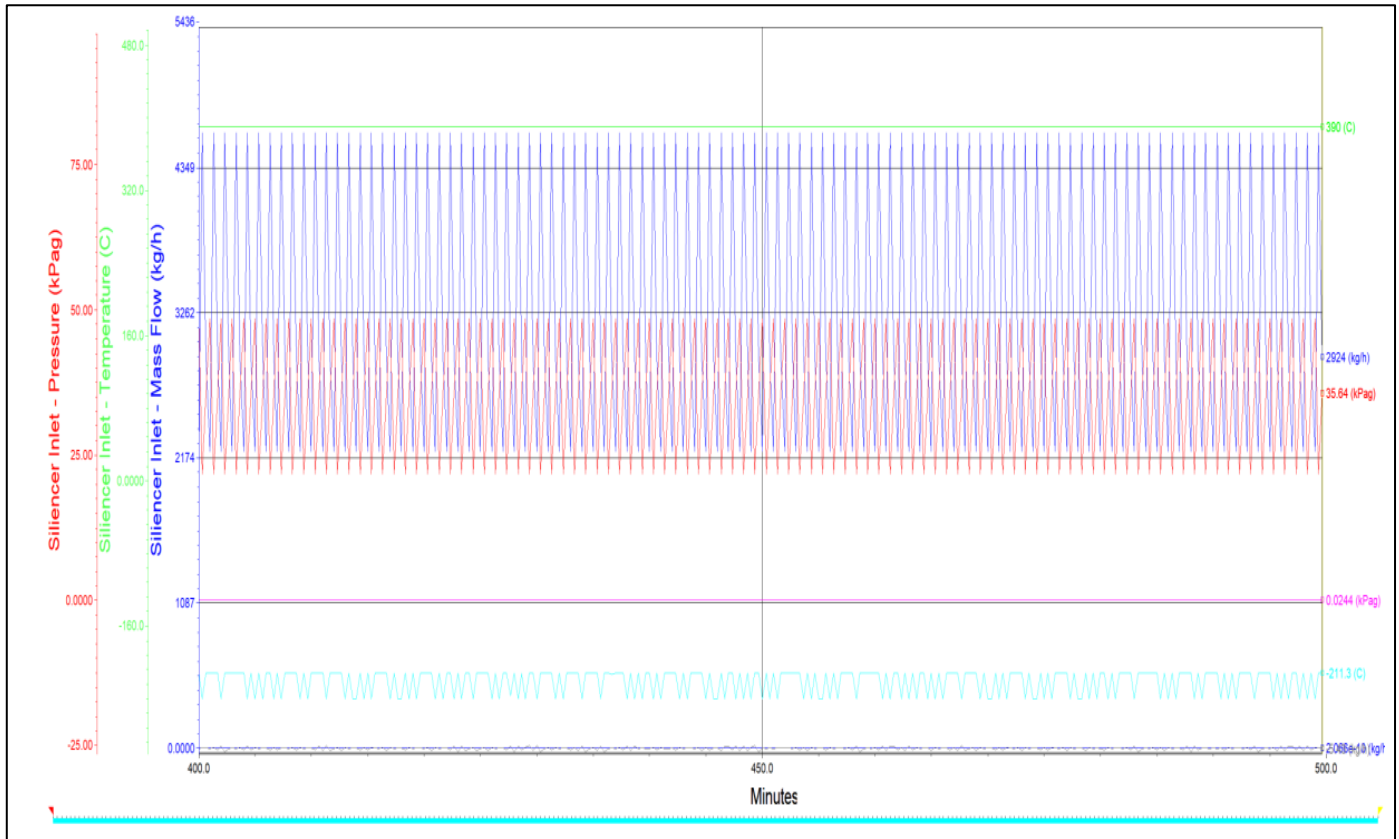


Fig 6 Case 3 Natural Gas @ 100% Load Dynamic Simulation Results

➤ Rupture Disc Sizing Analysis

- Rupture Disc 1 (Existing)

Table 6 Silencer Inlet RD

Parameter	Values
Size	DN400
Burst Pressure	40 kPag
Required Area	113.6 cm ²
Selected Area	993.1 cm ²
Rated Capacity	70,800 kg/hr

Table 7 New Rupture Disc 2 Proposed at WHB Inlet

Parameter	Values
Size	DN300
Burst Pressure	30 kPag
Required Area	132 cm ²
Selected Area	506.7 cm ²
Rated Capacity	31,080 kg/hr

The selected rupture discs were significantly oversized relative to the minimum requirements, providing substantial safety margins and ensuring adequate venting capacity during explosion events.

VI. CONCLUSION

This study successfully demonstrated the application of Aspen HYSYS steady-state and dynamic simulation techniques for evaluating explosion protection systems in reciprocating gas engine exhaust ducting.

Steady-state simulations confirmed acceptable operating performance under biogas and natural gas conditions, with exhaust back pressures well below engine trip limits and significant heat recovery achieved through the Waste Heat Boiler.

Transient analyses revealed that a single rupture disc arrangement may permit surge pressures approaching or slightly exceeding allowable duct design limits during deflagration events. The installation of a secondary rupture

disc at the WHB inlet substantially improved system protection by reducing peak surge pressures below 40 kPag.

[11]. NFPA 37:2021, *Installation and Use of Stationary Combustion Engines and Gas Turbines*.

The research confirms that a dual rupture disc arrangement provides the most effective protection strategy for long exhaust duct systems connected to waste heat recovery equipment. Aspen HYSYS dynamic modelling proved to be a valuable engineering tool for validating explosion protection designs and optimizing rupture disc placement.

RECOMMENDATIONS

The following recommendations were made as part of this study outcomes.

- Install multiple rupture discs in exhaust duct systems longer than 22 m.
- Position rupture discs at intervals of approximately 6 to 15 m.
- Provide a dedicated rupture disc at WHB inlet locations.
- Utilize staggered burst pressures of 40 kPag and 30 kPag.
- Maintain WHB bypass valve interlocks during engine startup.
- Adopt a preventive rupture disc replacement cycle of approximately three years.
- Verify actual commissioning pressure profiles against simulation results.

➤ Conflict of Interest

The authors declare that there is no conflict of interest associated with this study. The research was undertaken solely for technical evaluation and engineering design verification purposes.

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