D3.1 - Simulated operating conditions of the demonstrators

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HYINHEAT

Credits

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Abbreviations	Explanation
AFC	Air Fuel Combustion
OFC	Oxy-fuel Combustion
ASU	Air Separation Unit
PCV	Pressure Control Valve
FCV	Flow Control Valve
PFD	Process Flow Diagram
WP	Work Package
Demo	Demonstrator

Executive Summary

The HyInHeat project integrates H_2 as fuel for high temperature heating processes in energy-intensive industries, specifically targeting the aluminum and steel sector. The transition to H_2 fuel involves significant challenges, such as the need to redesign the supply infrastructure, burners, furnaces, and the heating process itself to ensure efficient utilization of H_s as fuel.

This deliverable encompasses the Task 3.1 and Task 3.2 of the Work Package 3 (WP3), which is dedicated to designing a safe and efficient H_2 and O_2 infrastructure. The Task 3.1 involves defining the on and off-design operating conditions for all the demonstrators, while the task 3.2 is regarding the steady-state simulations of H_2 and O_2 infrastructure from the point of supply to the point of utilization under defined operating conditions. The outcome of these tasks aims to provide an overview of the sizing of major equipment within H_2 and O_2 infrastructure and the simulations at different operating conditions, facilitating the subsequent detailed design for the demonstrators in WP5 and WP6.

The report is divided into the following chapters, which present all the work performed as part of the Task 3.1 and Task 3.2.

Chapter 1 describes the operating conditions for all the demonstrators, encompassing the flowrates and pressures of H_2 and O_2 along the supply infrastructure are meticulously defined. The data for this was obtained through a WP1 survey conducted in Task 1.1.

Chapter 2 presents a simplified process flow diagram of the H_2 and O_2 infrastructure, identifying the necessary equipment. The primary components include pipelines and control valves, which will be the focus of subsequent design and simulation efforts in the latter part of the report.

Chapter 3 delves into the detailed mathematical model for designing both pipelines and control valves, outlining the design criteria for sizing based on standard practices.

Chapters 4 and 5 provide detailed insights into the process simulation of H_2 and O_2 infrastructure using Aspen Plus, along with the simulation results for each demonstrator at various operating conditions.

Chapter 6 concludes the report, offering recommendations for the detailed design of equipment within the H_2 and O_2 infrastructure based on the comprehensive work undertaken throughout this deliverable.

The key findings of the process simulations conducted in Aspen Plus for H_2 and O_2 infrastructure, which involved the sizing and operation of pipelines and control valves, are as follows.

1. The transport of H_2 within pipelines can attain higher velocities, reaching up to 60 m/s, thanks to its lower density, thereby minimizing hydraulic losses. In contrast, the conventional upper limit for natural gas velocity in pipelines typically hovers below 20 m/s.
2. When it comes to transporting O_2 within pipelines, it is crucial to adhere to an upper velocity limit of approximately 15 m/s, as surpassing this threshold can lead to undesirable high hydraulic losses.
3. Adhering to standard industrial practices, the H_2 infrastructure recommends installing a maximum of two Pressure Reduction Valves in the primary letdown (decompression station). This primary letdown effectively reduces pressure from 200 barg to approximately 10 barg.
4. In the secondary letdown, it is advisable to implement only one pressure reduction stage for H_2, where the pressure is further reduced to typically less than 500 mbarg, aligning with the precise burner specifications.
5. Similarly, within the O_2 infrastructure, it is recommended to employ a single Pressure Reduction Valve for pressure letdown, ensuring alignment with the final requirements of the burner.
6. In both H_2 and O_2 systems, the incorporation of a dedicated Flow Control Valve is typically imperative to regulate the flow and meet the specific process heating requirements.
7. It is advisable to ensure that the nominal operating conditions are achieved with control valve openings close to 50%. This provides a substantial margin for effectively managing plant requirements even under off-design conditions.

8. When sizing control valves, a pivotal consideration is designing them to meet minimum and maximum flow conditions within valve opening range, spanning from 10% to 90%. This approach ensures optimal control at off-design operational scenarios.
9. The minimum pressure that can be achieved within H_2 tube trailer ranges from 25-35 bars with current configuration. Below this pressure, the pressure control valves are wide open and hence can no longer maintain the pressures at desired setpoint.

1 Introduction

Work Package 3 (WP3) is dedicated to the development of comprehensive documentation vital for designing a safe and effective hydrogen (H_2) and oxygen (O_2) supply system, specifically taylored for the HyInHeat project demonstrators. This system involves a distribution network that transports H_2 and O_2 from their production or storage sites to the final usage point, which is the burner in the furnace. In the HyInHeat demonstrations, all participants will use H_2 in a compressed gas form, typically transported at high pressures of approximately 200 bars in tube trailers or cylinders. The O_2 supply, on the other hand, will be in a liquid state, kept in cryogenic tanks and then converted to gas for use in the burner through an ambient evaporator located near the tank. Both H_2 and O_2 will then be delivered to the burner at the necessary operating conditions, passing through a series of pipes and valves.

The initial step of the WP3 is to define the nominal operating conditions for each demonstrator, encompassing critical parameters such as pressure, temperature, and flow rates. These operating conditions will serve as foundation for the design of process and sizing of the required equipment for H_2 and O_2 infrastructure. The upstream operating conditions that are pressures and temperatures of H_2 and O_2 supply depends on their delivery source such as tube trailers and liquid oxygen tanks, respectively. While the final downstream operating condition of both H_2 and O_2 depends on the design and operational specification of the burner itself. The flowrate of H_2 during the plant operation is determined by the burner size and may varies depending on the process heating requirements, while O_2 flowrate is determined through stoichiometry with certain amount of excess oxygen to ensure the complete combustion and to meet certain other process requirements as well.

The next step is to simulate each demonstrator case at these defined operating conditions using a commercial tool such as Aspen Plus which is a process simulation software. To perform the simulations, a simplified process flow diagram is developed first to identify major pieces of equipment inside the infrastructure such as storage tank, piping, and valves. Other ancillary components include filters and control instrumentation, but these are not included in the scope of this process simulation as it is devoted to only the sizing and simulation of major equipment encompassing the infrastructure. Therefore, the process simulation in Aspen Plus is mainly focused on the design and operation of piping and control valves inside the infrastructure.

1.1 Objectives

The primary objective of this report is to furnish a comprehensive overview of the results derived from process simulations pertaining to the H_2 and O_2 supply infrastructure, extending from the point of production or storage to the point of utilization. The simulations are meticulously conducted for each demonstrator using Aspen Plus, considering the distinctive operating conditions of each. The findings encapsulated in this report delve into various facets of the supply infrastructure, encompassing:

- **Pipeline Sizing:** The determination of the nominal pipeline size required for transporting H_2 and O_2 inside the plant
- **Flow Velocities:** Determination of flow velocities within the piping network to ensure optimal transport without compromising safety or efficiency
- **Pressure Drop Simulation:** An examination of pressure-drop within the pipelines under different operating conditions considering a hypothetical pipeline length
- **Valves Selection:** The selection of number of pressure reduction stages to get the desired pressures and selection of appropriate valves and their flow characteristic curves suitable for different operating conditions
- **Valves Operation:** Simulation of valves opening at various operating conditions during operation.

The comprehensive insights presented in this report are instrumental for the design of the H_2 and O_2 supply infrastructure, providing valuable guidance for selecting pipeline sizes and the control valves for each demonstrator to meet the operating conditions of the furnace.

1.2 Methodology

This report is based on the findings and results of Tasks 3.1 and 3.2 within Work Package 3. The following methodology was adopted to accomplish the tasks.

1.2.1 Data Collection

A comprehensive survey, led by WP1, was conducted to gather information related to Task 3.1 requirements. Demonstrators provided details on onsite H_2 and O_2 production, supply conditions, tentative pressure levels, burner specifications, HyInHeat experiment duration, and average fuel flowrates.

1.2.2 Flowrate Calculation

The maximum flowrate of H_2 and O_2 for each demonstrator was computed using stoichiometry based on burner specifications.

1.2.3 Supply Conditions Determination

Commercially available options, such as tube trailers for H_2 and tankers for Liquid O_2, were identified for H_2 and O_2 supply, as demonstrators opted against onsite production.

1.2.4 Operating Conditions Analysis

With information on operating conditions, including supply conditions, flowrates, and pressure levels for H_2 and O_2 transport, the sizing of key equipment, such as pipelines and control valves, was conducted.

1.2.5 Pipeline Sizing

Aspen Plus was utilized for direct pipeline sizing under maximum flowrate conditions, establishing a design criterion for both H_2 and O_2 pipelines.

1.2.6 Control Valve Sizing

Initial control valve sizing was performed manually using standard calculations in MS Excel. Detailed sizing and the selection of an appropriate flow characteristics curve were accomplished using Fisher Valve Sizing Manager.

1.2.7 Simulations in Aspen Plus

Utilizing the selected valve's flow characteristics curve and pipeline sizes, simulation was conducted in Aspen Plus to assess flow velocities, pressure drops, and valve openings under various operating conditions both on- and off-design.

This structured methodology ensured a systematic approach in accomplishing Tasks 3.1 and 3.2 within Work Package 3, allowing for a comprehensive analysis of the H_2 and O_2 supply infrastructure from production/storage to utilization.

1.3 Operating Conditions for Each Demonstrator

There are 10 demonstrators participating in the HyInHeat project. Among them 5 belong to the aluminum sector as shown in Figure 1 *and 5 belong to the steel sector as shown in* Figure 2*. Salient features of each demonstrator are described below separately. The operating conditions include H_2 and O_2 flowrate, pressures, and temperatures at various locations along the supply infrastructure which are listed in* Table 1 *and* Table 2*. The duration and frequency of the experiments for each demonstrator is listed in*

Table 3.

The temperature of both H_2 and O_2 streams transported inside the plant is not of interest as it typically varies between -20 °C to +50 °C depending on the ambient conditions.

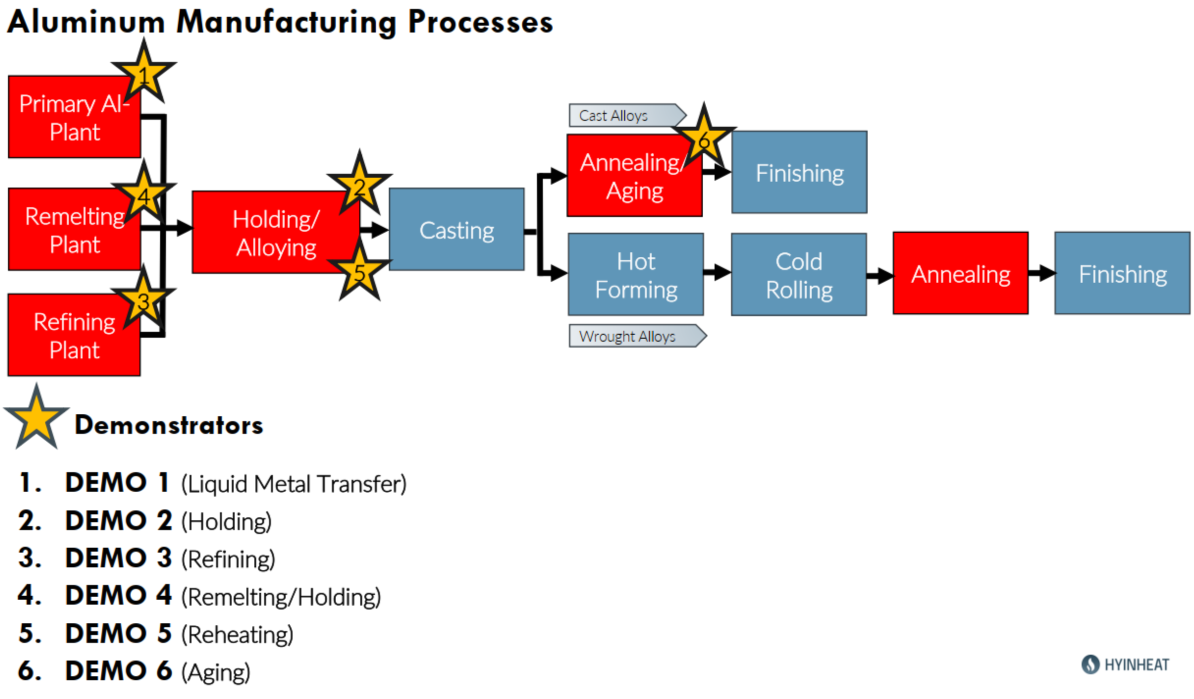

Figure 1 Aluminum sector demonstrators mapped across the production value chain

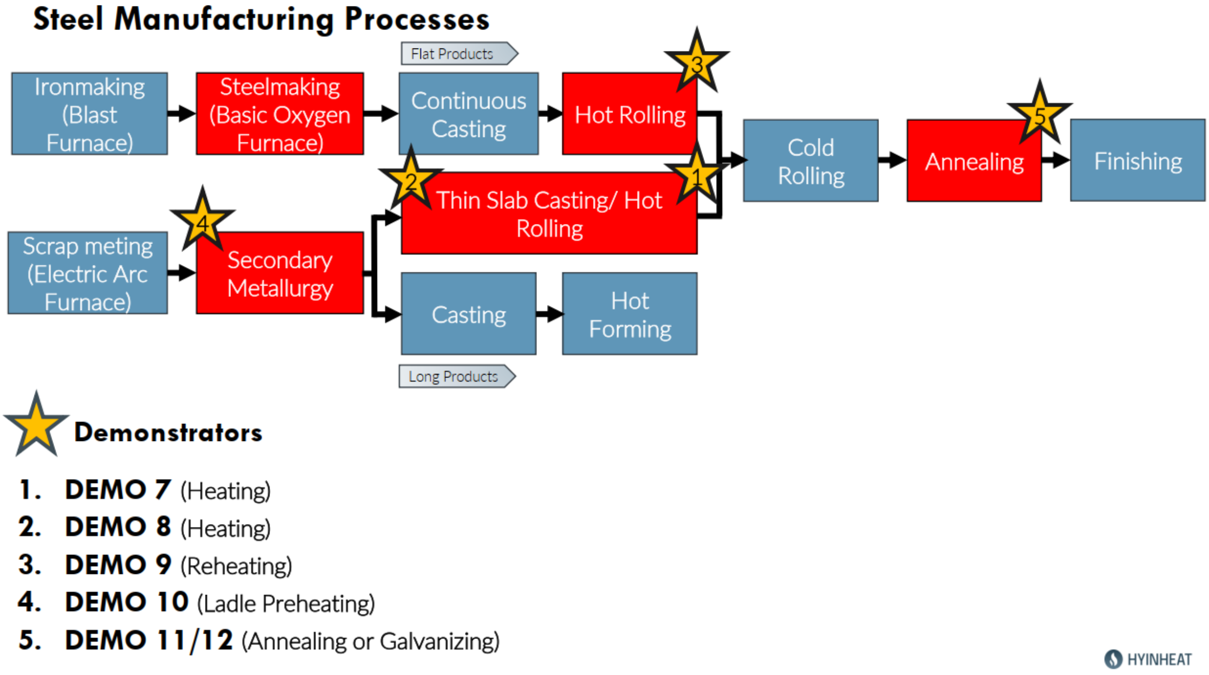

Figure 2 Steel sector demonstrators mapped across the production value chain

1.3.1 DEMO 1

A 6-t capacity ladle pre-heating facility for holding the aluminum metal at high temperature to be transferred to the cast house. It is a batch process with a 20 h cycle time. The current burner(s) is running on NG/Air, and it will be retrofitted to oxy-fuel combustion.

1.3.2 DEMO 2

Demo 2 will perform a design study on 65t holding furnace. It has got 3 burners of 1750 kW which will be theoretically retrofitted to H_2/O_2 burners.

1.3.3 DEMO 3

It is a 1-t capacity rotary furnace to melt aluminum scrap. It is a batch process with a 4 h cycle time. The current NG/O_2 burner is to be retrofitted with an H_2/O_2 burner.

1.3.4 DEMO 4

It is a 12-t capacity reverberatory furnace installed in a pilot cast house used for melting and holding aluminum. It is a batch process with 4 h of melting and 4 h of holding. The current NG/O_2 will be retrofitted with an H_2/O_2 burner.

1.3.5 DEMO 5

It is a 400-t capacity aluminum ingots preheating furnace equipped with 60 radiant tube burners, total power 11 MW. It is a complete design study.

1.3.6 DEMO 6

It is a rotary artificial aging furnace with a capacity of around 1.248-t. It has a batch process of 75 min with 45 min of heating and 30 min of holding. The current NG/Air burner will be replaced with an H_2/Air (and O_2) burner.

1.3.7 DEMO 7

It is a tunnel furnace with a 150-t capacity to heat and homogenize the temperature of steel slabs. It is a batch process with 5-6 slabs per heat cycle. The average cycle time is 0.8 h with 15-20 mins per slab. It has two lines with each line equipped with 124 NG/Air recuperative burners. Some burners will be retrofitted to H_2/Air burners.

1.3.8 DEMO 8

It is a walking beam reheating furnace to produce long steel products. It has a continuous process with a 180-210 t/h capacity. It is equipped with 61 NG/air burners. Some burners will be retrofitted to oxy-fuel burners.

1.3.9 DEMO 9

It is a continuous operation walking beam furnace for reheating with a capacity of 3t/h. It is equipped with 6 burners which can operate on Oil, Blast Furnace gas (BFG) and air fuel or oxy-fuel combustion. As part of the demonstration, different tests will be performed with air-fuel combustion (AFC), AFC+O_2 and oxy-fuel combustion (OFC) with H_2.

1.3.10 DEMO 10

It is a ladle furnace preheater with a 1 t capacity. The current CO/air burner is to be retrofitted with Oxy-fuel combustion.

1.3.11 DEMO 11

It is a test-rig for demonstration of real size burners with indirect heating (radiant tubes) furnace. Trails will be performed with NG/H_2 blends with air/O_2 for both radiant tubes and direct burners.

1.3.12 DEMO 12

It is a test-rig for demonstration of real size burners with direct heating furnace. Trails will be performed with NG/H_2 blends with air/O_2 for both radiant tubes and direct burners.

Table 1 Summary of burner data and their respective maximum flow rates for each demonstrator

	Demo1	Demo2[1]	Demo3	Demo4	Demo5[1]	Demo6	Demo7	Demo8	Demo9	Demo10	Demo11 Demo12
Burner Power (kW)	80-100	1750	800	2500	11,000[2]	170	240	5000	400-500	1500	160 1200
N. Burner Replaced	1	3	1	1	60	1	10-16	4	6	1	2 2
New Burner Fuel	H_2/O_2	H_2/O_2	H_2/O_2	H_2/O_2	H_2/O_2	NG/H_2 Air	H2/Air	H_2/O_2	H_2/O_2 H_2/Air	H_2/O_2	NG/H_2 Air/O_2
H_2 Flowrate (Nm^3/h)	33.3	1750	266.7	833	3666	56.7	1040	6667	500	500	120 400
O_2 Flowrate (Nm^3/h)	17	892	136	425	1870	N/A	N/A	3400	255	255	61.2 204

Table 2 Summary pressure conditions (bars) at various locations for each demonstrator (red values are assumed).

	Demo1	Demo2	Demo3	Demo4	Demo5	Demo6	Demo7	Demo8	Demo9	Demo10	Demo11 Demo12
H_2 Pressure at supply	200	200	200	200	200	200	200	200	200	200	200
H_2 Pressure inside plant	4	10	10	10	10	10	10	10	15	10	4
O_2 Pressure at supply	18	18	18	18	18	N/A	N/A	18	18	18	18
O_2 Pressure inside plant	15	15	15	15	15	N/A	N/A	15	15	15	15
H_2 Pressure at burner	1	*	*	1.15	*	*	*	3	1	*	*
O_2 Pressure at burner	4	*	*	8	*	*	*	3	4	*	*

Table 3 Trials duration and frequency for each demonstrator

	Demo1	Demo2	Demo3	Demo4	Demo5	Demo6	Demo7	Demo8	Demo9	Demo10	Demo11 Demo12
Trial Duration (h)	4	-	4	8	-	2	2	2	12	-	24
Frequency (per day)	1	-	1	1	-	1	1	1	1	-	1

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[1] Design Study

[2] Total Power (sum of all burners)

Red to be finalized by the demonstrators

2 Infrastructure for H_2 and O_2 from Point of Production to Utilization

As stated in the introduction chapter, the H_2 and O_2 supply infrastructure starts from the point of production, where the H_2 and O_2 production refers to the onsite electrolyzers. However, as part of the demonstration within HyInHeat project, the onsite production of H_2 and O_2 is not envisaged by the demonstrators. Therefore, the infrastructure designed and simulated in this report starts from the point of supply till the point of utilization.

2.1 H_2 Infrastructure

The H_2 infrastructure starts from the tube trailers typically connected at the plant gas station which is supplied at very high pressure around 200 bar. This high pressure needs to be reduced to a lower pressure suitable for the transport inside the plant in the primary gas letdown station (Decompression Station). In the primary letdown station, there are two pressure reduction stages to reduce the pressure from 200 bar to around 8-15 bar depending on the demonstrator. This low pressure H_2 is then transported inside the plant via pipeline to the final point of utilization which is the burner skid. Here the pressure of H_2 is further reduced to meet the burner pressure specification in a single stage pressure reduction. Far downstream, there is also a flow control valve to control the flow of H_2 as required by the burner or the process heating conditions. This H_2 infrastructure is shown in a simplified process flow diagram in Figure *3*.

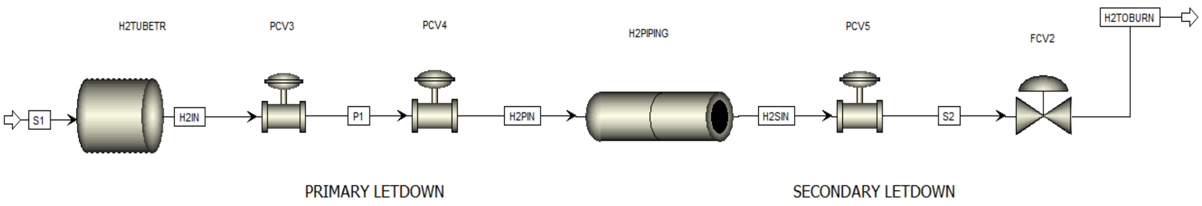

Figure 3 H_2 supply infrastructure process flow diagram

The main components of the simplified process flow diagram for H_2 supply are the tube trailer, control valves, piping, and the burner itself. In the detailed H_2 infrastructure, there are other ancillary components like the filters, pressure safety valve, instrumentation for the measurement and control such as pressure, temperature, and flowrate indicators and transmitters. Other than the control valve for pressure and flow control described above, there are some isolation/shut-off valves typically at the upstream and downstream point to stop and start the flow. There are also some small tapping connections in the pipeline for the safe vents and drains. However, the focus of this report is only on the major equipment in H_2 infrastructure, which are listed below.

2.1.1 Major Equipment for H2 infrastructure

1. H_2 Tube trailer
2. Control Valves
3. Piping

2.2 O_2 Infrastructure

The O_2 infrastructure starts from the cryogenic liquid oxygen tank. In the tank, O_2 is present in the liquid state at around -183°C. This liquid oxygen is heated in an ambient air vaporizer to change into the gaseous state. This vaporizer is either directly mounted with the tank known as clip-on design or it is a separate ambient vaporizer if the required flowrate of O_2 is high. The gaseous O_2 pressures which is typically at 15-18 bar is then adjusted for transport inside the plant. The typical pressure for transport inside plant is around 15 bar, however it may vary for the individual demonstrators. O_2 is then transported to the ultimate point of use which is the burner skid. Here, first the pressure is further reduced to meet the burner pressure specifications in a single stage pressure reduction. There is also a flow control valve at the downstream to control the flow of O_2 as required by the process conditions. The O_2 infrastructure is shown in a simplified process flow diagram in Figure 4. Other additional components of the detailed O_2 infrastructure are like the ones described for the H_2 infrastructure, however the attention of this report is devoted to main equipment only.

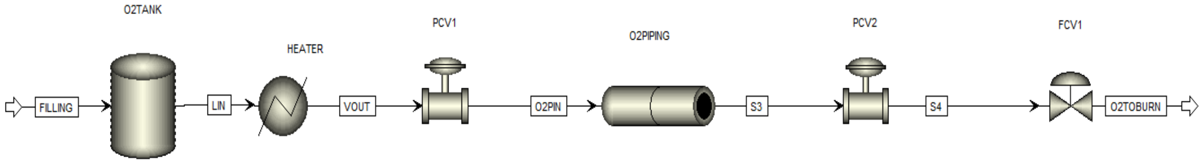

Figure 4 O_2 supply infrastructure process flow diagram

The main components of the simplified process flow diagram for O_2 supply are the Liquid Oxygen Tank (LOX), air heated vaporizer, control valves, piping, and the burner itself. Below is the list of major equipment in O_2 infrastructure.

2.2.1 Major Equipment for O_2 infrastructure

1. Liquid Oxygen Storage tank
2. Ambient air vaporizer
3. Control Valves
4. Piping

3 Mathematical Modelling of the System

In this chapter, each major unit operation is described in detail and the criterion to decide the sizing of these unit operations and their mathematical model are discussed.

3.1 Valves

The control valve is the device that controls the flow of the fluid (gas, liquid, and slurries) inside the process thereby regulating other process parameters such as pressure, temperature inside the process depending on the requirement. A valve creates restriction to the fluid flow and due to fluid-dynamic effects it causes pressure drops. The pressure drop is directly proportional to the flowrate, and the flowrate is a function of the valve opening. This characteristic of the valve is given by its manufacturer in the form of characteristic curves which tell the relation between the flow coefficient and the valve opening.

Proper sizing of the valves is extremely important for reliable and cost-efficient operation. Under-sizing the valve will result in a valve that is not able to process the required flowrate, and the process will be starved. Over-sizing the valve makes the equipment cost higher, and it may also result in unstable operating conditions, that leads to a difficult control of the process.

Another important issue to consider in the valve selection is the choking inside the valve. Indeed, the valve restriction creates high velocities inside the valve and when the velocity is sonic or above, the valve is said to be choked. In choked conditions, the flow through the valve can no longer be changed by varying the downstream pressure. Also, the choking conditions can sometimes damage the valve.

3.1.1 Valve Sizing Mathematical Model

The valve flow coefficient, $C_V \left(\frac{gpm}{psi^{0.5}}\right)$, tells the capacity of fluid flow (gas or liquid) through the valve at 100% open condition relative to the pressure drop. It is defined as the flowrate of water in gallons per minutes at 60 °F through a fully open valve at a pressure drop of 1 psi. The basic equation for C_V is given as follows

$$Q = C_V \sqrt{\frac{\Delta P}{G}} \tag{3.1}$$

where $\Delta P\ (psi)$ is the pressure drop across the valve, $G\ (-)$ the specific gravity of the fluid, and $Q\ (gpm)$ the flowrate of the fluid.

Other parameters such as the geometrical correction factor $F_p\ (-)$ also need to be incorporated in the equation to account for fittings losses such as the reducer, expander or any elbow connected directly between the pipeline and the valve as follows

$$F_P = \left[1 + \frac{\sum K}{N}\left(\frac{C_V}{d^2}\right)\right] \tag{3.2}$$

where $N\ (-)$ is the numerical constant for unit conversion, $d\ (inch)$ the nominal valve size, and $\sum K\ (-)$ the velocity head loss for all the fittings attached between the piping and the valve calculated using standard formulas.

For the gas service, due to the compressible effects we need to introduce the expansion factor $Y\ (-)$ as

$$Y = 1 - \frac{X}{3\ F_K X_T} \tag{3.3}$$

where $X\ (-)$ is the actual pressure drop ratio, i.e. the ratio of pressure drops across the valve to inlet pressure, $F_K\ (-)$ the ratio of specific heat factors, i.e. $k/1.4$ being $k(-)$ the specific heat of the gas, and $X_T\ (-)$ the terminal pressure drop ratio required to produce a critical flow (choked condition) through the valve, that is also a function of the valve opening.

The value of Y ranges from 2/3 at fully choked conditions to 1 at subsonic conditions. Therefore, incorporating these additional factors, the modified equation for the flow coefficient C_V of compressible gas is given as follows

$$C_v = \frac{Q}{N_7 F_p P_1 Y \sqrt{X/_{G_g T_1 Z}}} \tag{3.4}$$

where $Q\ (Nm^3/h)$ is the volumetric flowrate, N_7 the numerical constant for the selected system of units, $P_1(bar)$ the upstream pressure, $G_g\ (-)$ the gas specific gravity, $T_1(K)$ the inlet temperature, $X\ (-)$ the actual pressure drop, and $Z\ (-)$ the compressibility factor. The desired valve is then selected from the manufacturer database once the values of C_V are determined at different operating conditions.

3.1.2 Valves Choking

When the pressure drop across the valve is greater than terminal pressure drop ratio X_T at a certain valve opening, the valve is said to be in choked conditions. With constant upstream pressure, further increasing the pressure drop by decreasing the downstream pressure will not change the flowrate any further. X_T is provided by its manufacturer, measured by testing the valve and is provided as a function of the percentage valve opening, and is definition is as follows

$$X_T = \frac{\Delta P_{critical}}{P_1} \tag{3.5}$$

where $\Delta P_{critical}$ is the maximum pressure drop across the valve just before the choking occurs. Since the sonic velocity of H_2 is approximately 4 times of the typical flammable gases such as natural gas, attention must be taken in the selection of the control and relief valves due to possible erosion and abrasion when operating near the sonic conditions.

3.2 Piping

The purpose of the piping is to transport the fluid from one location to another. In the process industry, pipeline sizing criteria is primarily based on two important parameters: maximum velocity and pressure drop inside the pipeline.

3.2.1 Pressure Drop Criteria

The criteria to decide the pressure drop limit along the pipeline depends on the actual process requirements itself. There are some processes where a certain pressure level strictly needs to be met at the end of the pipeline for the downstream equipment to operate properly. Also, there are some recommended practices and standard guidelines for pressure drop limit while designing the pipeline for different service conditions and those guidelines are normally based on economic reasons.

On the contrast, there are some cases when pressure drop inside the pipeline is not a critical factor for designing because the upstream pressure is so high that the pressure drop inside the pipeline is not a limiting factor and the main goal of the design is to reduce the system cost as much as possible. In this project, the pressure drop is not critical thanks to the high upstream pressure of both H_2 and O_2 supply.

3.2.2 Maximum Velocity Criteria

The velocity of gas inside the pipeline should not exceed a certain limit to avoid noise, vibration, and erosion problems. Different standards provide guidelines and limits for the maximum velocity. According to the NORSOK P-002 standard [1], for gas services the velocity should not exceed the one calculated with the below equation or 60 m/s, whichever is the lowest

$$V = 175\left(\frac{1}{\rho}\right)^{0.43} \tag{3.6}$$

where $\rho\ (\frac{\text{kg}}{\text{m}^3})$ is density of the fluid, and $V\ (\frac{m}{s})$ is maximum allowed velocity. However, the above criterion is only valid for clean gases that have no solid particles present inside the gas medium. For two-phase gas-liquid flows, e.g. gases with some liquid drops inside, the maximum velocity should not exceed the erosional velocity $v_e \left(\frac{ft}{s}\right)$ which is given by following correlation provided by API RP 14 E [2].

$$v_e = c/\sqrt{\rho} \tag{3.7}$$

where $c\ (\mathrm{lb/s/ft^2})$ is an empirical constant varying between 100-250 based on service conditions, and $\rho\ (\mathrm{lb/ft^3})$ the gas density. The rule of thumb is that the velocity of pipeline should be 40-50% of the erosional velocity.

On the contrary, there are some other guidelines such as the Asia Industrial Gases Association publication on Hydrogen pipeline systems [3], which states that there is no special restriction on maximum velocity limit for the H_2 Pipeline other than underlying economics of operating costs and system costs.

Since the pressure drop along the pipeline is also a function of the velocity as shown in Eq 3.8, therefore care must be taken to avoid very high velocities. In this project, the maximum velocity is set equal to 60 m/s and 15 m/s for H_2 and O_2 pipelines, respectively. The limit of O_2 is lower because of the very high hydraulic losses at higher velocities.

3.2.3 Pipeline Pressure Drop Mathematical Model

The pressure drop inside the pipeline is calculated by the well-known Darcy-Weisbach equation as

$$\Delta P = f\ \frac{L}{D}\ \rho\ \frac{V^2}{2} \tag{3.8}$$

where $f\ (-)$ is the Darcy friction factor, $L\ (m)$ the length of pipeline, $D\ (m)$ the hydraulic diameter which for the circular cross-section is the inner diameter of the pipeline, $\rho\ (\frac{kg}{m^3})$ the average density, $V\ (\frac{m}{s})$ the average velocity inside the pipeline, and $\Delta P\ (Pa)$ the total pressure drop. The velocity inside the pipeline is be determined as follows

$$V = \frac{4\ Q}{\pi\ D^2} = \frac{4\ m}{\rho\ \pi\ D^2} \tag{3.9}$$

where $Q\ \left(\frac{m3}{s}\right)$ is the volumetric flow rate, $D\ (m)$ the pipe internal diameter and $m\ (\frac{kg}{s})$ the mass flow rate.

The Darcy friction factor f is a function of two parameters: the relative roughness of the pipeline (ε/D) and the Reynolds' number $Re\ (-)$ which is defined as follows

$$Re = \frac{\rho\ V\ D}{\mu} = \frac{4\ \dot{m}}{\pi\ D\ \mu} \tag{3.10}$$

where $\mu\ (Pa.s)$ is the dynamic viscosity of the fluid inside the pipeline. For fully developed laminar flows, i.e. Reynolds' number below 2300, the friction factor is just a function of the Reynolds' number and is calculated as follows

$$f = \frac{64}{Re} \tag{3.11}$$

For Reynolds' number above 2300, the friction factor is calculated using the well-known Colebrook-White equation as follows [4].

$$\frac{1}{\sqrt{f}} = -2log_{10}\left(\frac{\varepsilon/_D}{3.7} + \frac{2.51}{Re\ \sqrt{f}}\right) \tag{3.12}$$

Due to the implicit form of f in the Colebrook-White equation, the equation cannot be directly solved. Therefore, root finding numerical methods such as Newton-Raphson Method should be required to compute f. However, different explicit correlations have been developed for the friction factor calculation that approximate the Colebrook-White equation. One of them is the Mozon-Romeo-Royo equation [5] which is considered good with an average deviation of less than 5% from the Colebrook-White equation

$$\frac{1}{\sqrt{f}} = -2log\left\{\frac{\varepsilon/_{D}}{3.7065} - \frac{5.0272}{Re}\left[\frac{\varepsilon/_{D}}{3.827} - \frac{4.567}{Re}log\left(\left(\frac{\varepsilon/_{D}}{7.7918}\right)^{0.9924} + \left(\frac{5.3326}{208.815 + Re}\right)^{0.9345}\right)\right]\right\} \quad 3.13$$

Once the friction factor is computed via the above equation, the pressure along the pipeline is determined and compared with the design requirements. If the pressure drop does not satisfy the design requirements, the pipeline size should be changed to meet the desired operating conditions.

4 Steady-state H_2 and O_2 infrastructure Process Simulation Setup

This chapter outlines in detail the process simulation of the H_2 and O_2 infrastructure, using Aspen Plus as process simulation software for the steady-state analysis. The primary objective of the simulation is to evaluate the velocity and pressure drops inside the pipeline by properly sizing the pipeline, and to simulate the valves opening and the pressure drop across the valves at different operating conditions while ensuring appropriate valve sizing. The initial section provides an overview of the Aspen Plus setup, followed by an in-depth description of the actual model describing each component. In the end, the on-design and off-conditions considered for simulating different cases are described.

4.1 Aspen Plus Setup

Aspen Plus has been widely used in the industry for performing process simulations. In Aspen Plus, each simulation model is a combination of streams and blocks that represent the whole process. The streams in our case represent the material flows of H_2 and O_2, which thermodynamic properties are determined by the software using an equation of state that must be appropriately selected by the user. The property method adopted for this simulation is the Redlich-Kwong-Soave (RKS) equation of state. The input streams, i.e., both H_2 and O_2, are to be completely described in terms of flowrate, temperature, pressure, and composition. The blocks are the unit operations which are essentially the pipes and the valves for our simulation. There are other blocks in the model as well, e.g., storage tanks and air vaporizer, but these are not modelled in detail in the context of this simulation because out of the scope of this work. For the pipeline block, the input parameters required by the software are the pipe size, thickness, length, and fittings details. For the valve block, the valve flow characteristic curve and outlet pressure are required as an input to the software. After all the input streams and blocks required inputs are completely defined, the model can be run, and Aspen Plus solves the system simulation.

4.2 Simulation Model Description

In this section, the model developed for H_2 and O_2 infrastructure is described in detail, starting from the simulation model inputs. Then, the model blocks and the required outputs from the simulation are discussed.

4.2.1 Simulation Model Inputs

The model starts from two parallel input streams of H_2 and O_2 as shown in Figure 5. The H_2 inlet stream (represented as H2TTIN) is coming from the H_2 tube trailer. The stream pressure is defined equal to the pressure of the tube trailer, and for the steady-state on-design simulation it is kept as a constant equal to 200 bar for the on-design case. The flowrate of the H_2 inlet stream is imposed in the Aspen Plus stream properties equal to the one corresponding to the demonstrator's burner maximum power requirement as listed in Table *1*. The temperature for the H_2 inlet stream is considered equal to the ambient temperature. The O_2 inlet stream (represented as O2TIN) input is defined in a similar way, with both pressure and temperature equal to that of the liquid oxygen tank, which are typically 18 bar and -183°C, respectively.

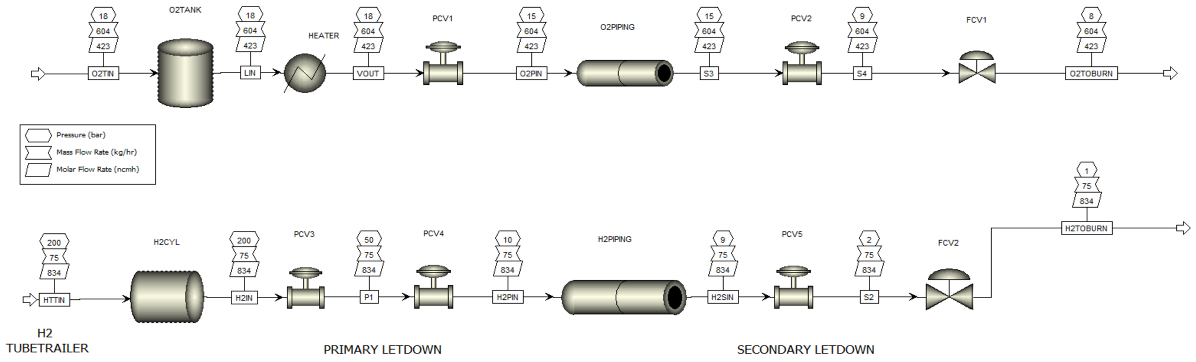

Figure 5 H_2 and O_2 infrastructure Aspen Plus flowsheet

4.2.2 Simulation Model Blocks

In this section, detailed descriptions for each block within the H_2 and O_2 infrastructure as shown in Figure *5* will be provided. As mentioned earlier, the O_2 infrastructure includes the O_2 storage tank (represented as O2TANK) and the ambient vaporizer (represented as AMBEVAP), but these blocks are not modelled extensively in this simulation. Downstream of the ambient vaporizer, the O_2 thermodynamic properties are configured to ensure it exits in the vapor phase at ambient temperature. Additionally, in the H_2 infrastructure, the first block, the H_2 storage pressure tank (represented as H2CYL), is not extensively modelled in this simulation. All other blocks will be described, including the pressure control valves (PCV), flow control valve (FCV), and the H_2 and O_2 pipelines.

4.2.2.1 Pressure Control Valves (PCV)

The purpose of PCV is to regulate the pressure of the fluid flowing in the process. In the H_2 infrastructure, there are three pressure control valves. Two valves are installed between the H_2 inlet from the tube trailer and the piping that transports the H_2 at some pressure inside the plant, while the third valve is at the downstream before the burner. For all three PCVs, the valve flow characteristic and the pressure drop ratio factor are inserted in the Aspen Plus model as valve inputs and the required pressure at the outlet of the valve is defined. In the O_2 infrastructure, there are two PCVs. The first one is between the air vaporizer and the piping which must transport the O_2 inside the plant, and the second one is between the pipeline downstream and the burner to achieve the desired pressure for the burner operation. For both the PCVs, the valve flow characteristic and the pressure drop ratio factor are inserted in the Aspen Plus model as valve inputs and the required pressure at the valve outlet is defined. As outlined before, the purpose of these PCVs is to regulate the downstream pressures regardless of the flowrates.

For all these valves, the C_V at nominal flow conditions is calculated using the method described in section 3.1.1. However, the complete flow characteristic curve is selected from the Fisher Valve Sizing Manager software by choosing an appropriate valve that can meet both maximum and minimum operating conditions within 20%-80% valve opening.

4.2.2.2 Flow Control Valves (FCV)

The purpose of FCVs is to regulate the flowrate of both H_2 and O_2 streams as required by the burner. For both H_2 and O_2 infrastructure, at the upstream of the burner/s there is a flow control valve. In the steady-state simulation, the flowrate for both H_2 and O_2 are imposed at the inlet streams. Therefore, the purpose of these valves inside the simulation is to simulate the valves opening and pressure drops at various inlet flowrates, during both the on-design and off-design conditions. All the input parameters for the FCVs in the Aspen Plus model are identical to what is described for the PCVs. Moreover, the C_V at the nominal flow condition is calculated in same way and the suitable complete flow characteristic curve is selected from the manufacturer sizing software.

4.2.2.3 Piping

The purpose of the piping is to transport H_2 and O_2 from the storage point to the burner skid. The pipe block inside Aspen Plus requires defining the pipeline size, length, and thickness as necessary input. Since the pipeline sizing is the result of the simulation, therefore the simulation is iterative. Different pipeline sizes will be chosen until the required design criteria described in section 3.2 is met. The pipeline length is set equal to 100 meters for the preliminary simulations as the actual length for the demonstrators is unknown. The pipe wall thickness is considered as schedule 40 for the preliminary simulations 41.

4.2.3 Simulation Model Output

The required outputs of this simulation are the following:

1. Sizing of the pipelines, velocities inside the pipelines and pressure drop across the pipelines for both H_2 and O_2 infrastructure.
2. Selection of appropriate valves flow characteristic curve to ensure optimal valves opening at different operating conditions.

4.3 Description of On-design and Off-Design Conditions

4.3.1 On-design Conditions

Following are the on-design conditions.

1. H_2 inlet stream pressure equal to the maximum pressure of 200 bar and temperature equal to ambient one
2. O_2 inlet stream pressure equal to the maximum pressure of 18 bar and temperature equal to freezing temperature. Downstream of the ambient vaporizer the temperature is equal to ambient.
3. H_2 and O_2 streams flowrate equal to the nominal flowrate, corresponding to 100% load i.e., maximum burner power listed in Table *1*.

4.3.2 Off-design conditions

Following are the off-design conditions considered for the simulation:

1. Steady-state simulations at H_2 supply pressure levels of 100, 80, 50, 35, and 25 bars to assess the impact of decreasing H_2 supply pressure in as the tube trailer is being consumed.
2. Simulate lower H_2 and O_2 flowrates, equivalent to 75% of full load conditions, to evaluate the operational feasibility of the pipeline and control valves under these reduced flow conditions.
3. Simulate higher H_2 and O_2 flowrates, corresponding to 125% of full load conditions, to assess the performance of the pipeline and control valves under increased flow conditions.

The simulation aims to verify the operability of the pipeline and control valves under different operating conditions and assess pressure drop, velocity, and valve behavior.

5 Simulation Results and Discussion

In this chapter, the outcomes of the simulations performed in Aspen Plus are presented. The first section illustrates the results pertaining to pipeline which includes pipeline nominal sizes, velocity inside the pipeline and total pressure drop for an assumed length of 100 meters for each demonstrator. In the subsequent section, valves sizing results, selected valves flow characteristics curve and valves opening at various operating conditions are described.

5.1 Pipeline Sizing, Flow Velocity and Pressure Drop Results

As outlined in section 3.2, the sizing of the pipeline is based on two important considerations: pressure drop and fluid velocity within the pipeline. The pressure drop is not a critical concern given the high pressure of the H_2 and O_2 supply in comparison to burner pressure conditions. On the other hand, it is necessary to take into consideration that in the pipeline compressible gases flow. Thus, the outlet velocity of the pipeline exceeds the inlet velocity due to the rise in volumetric flow rate caused by the effects of pressure drop and compressibility. To ensure that the system operates optimally, it is imperative that below a certain limit the pressure drop across the pipeline, which is also necessary to prevent a significant difference between the outlet velocity and the inlet velocity of the pipeline. Section 3.2.1 has already specified the maximum permissible velocity limits for both H_2 and O_2 services as 60 m/s and 15 m/s, respectively.

For H_2 pipeline sizing, the pressure considered for transport inside the plant is 10 bar for the initial sizing of pipeline and the simulation for all demonstrators. The typical pressure range is around 9-15 bar; however, it may vary from case to case. The pipeline sizes can only be selected from the commercially available standard nominal pipe sizes (NPS) chart such as listed in AMSE B36.10 [6]. The results, including H_2 pipeline NPS, velocities, and pressure drop for each demonstrator, are presented in Table 4.

Table 4 H_2 supply pipeline sizes, velocity, and pressure drop for each demonstrator

Demo	Equipment	Burner/s	H_2 Flowrate (Nm3/h)	H_2 Flowrate (kg/h)	Pressure (bar)	NPS	Erosion Velocity (m/s)	Inlet Velocity (m/s)	Outlet Velocity (m/s)	ΔP 100m (bars)
Demo1	Preheating Station	1	33.3	2.99	4	0.25-IN	214	38	52	1.07
Demo2	Holding Furnace	3	1750	157	10	1.5-IN	135	41	42	0.37
Demo3	Rotary Furnace	1	267	24	10	0.5-IN	135	42	49	1.36
Demo4	Reverb Furnace	1	833	75	10	1-IN	135	46	50	0.82
Demo5	Reverb Furnace	1	3666	329	10	2-IN	135	52	54	0.45
Demo6	Artificial Aging Furnace	1	56.7	5.09	10	0.25-IN	135	26	29	1.07
Demo7	Tunnel Furnace	10	800	72	10	1-IN	130	44	48	0.75
Demo8	Walking Beam Furnace	4	6666.6	599.9	10	3-IN	130	43	44	0.18
Demo9	Walking Beam Furnace	3	500	45	15	0.75-IN	130	30	31	0.69
Demo10	Ladle Preheating	1	500	45	10	0.75-IN	130	44	50	1.06
Demo11	Indirect heating	2	120	10.8	4	0.5-IN	214	47	58	0.7
Demo12	Direct Heating	4	400	35	4	1-IN	214	55	63	0.5

For O_2 pipeline sizing, the pressure considered for transport inside the plant is 14 bar for the initial sizing of pipeline and the simulation. This is the typical pressure value after the ambient air vaporizer; however, it may vary for each demonstrator. The results, including O_2 pipeline NPS, velocities, and pressure drop for each demonstrator are presented in Table 5.

Table 5 O_2 supply pipeline size, velocity, and pressure drop for each demonstrator

Demo	Equipment	Burner/s	O_2 Flowrate (Nm3/h)	O_2 Flowrate (kg/h)	NPS @ 15 bar	Erosion Velocity @ 15 bar	Inlet Velocity (m/s)	Outlet Velocity (m/s)	ΔP 100m (bars)
Demo1	Preheating Station	1	17	24	0.25-IN	27	5.1	5.4	0.93
Demo2	Holding Furnace	3	892	1273	2-IN	27	8	9	0.27
Demo3	Rotary Melting Furnace	1	136	193	0.75-IN	27	7.99	8.41	0.76
Demo4	Reverb Melting Furnace	1	550	781	1.5-IN	27	8.46	8.67	0.36
Demo5	Reverb Melting Furnace	1	1870	2669	2-IN	27	17	19	1.15
Demo6	Artificial Aging Furnace	1	Only Air will be used in the demonstration						
Demo7	Tunnel Furnace	10	Only Air will be used in the demonstration						
Demo8	Walking Beam Furnace	4	3400	4828	3-IN	7	14.40	14.87	0.47
Demo9	Walking Beam Furnace	3	255	362	1-IN	27	9.24	9.72	0.75
Demo10	Ladle Preheating	1	255	362	1-IN	27	9.24	9.72	0.75
Demo11	Indirect heating	2	61	86	0.5-IN	27	6.31	6.61	0.69
Demo12	Direct Heating	4	204	289	1-IN	27	7.9	8.2	0.51

5.2 Valve Sizing, Rated C_V and Valve travel Results

As previously outlined in Section 0, the H_2 infrastructure features four primary control valves, comprising three pressure control valves (PCVs) and one flow control valve (FCV). Correspondingly, within the O_2 infrastructure, three key control valves are present, including two pressure control valves and one flow control valve. In the following sections, the calculated C_V values for each valve under nominal flow conditions are presented. Then, the second section shows the flow characteristic curves and the results of valve percentage openings obtained from the simulations conducted at various operating conditions.

5.2.1 C_V Results at Nominal Condition

The C_V at nominal conditions are calculated using the standard metho described in section 3.1.1. In Table 6, the upstream pressure $Pup\ (bar)$, downstream pressure $Pdn\ (bar)$, and C_V at the nominal flowrate for each control valve of the H_2 infrastructure is provided. As described earlier, the nominal condition corresponds to 100% load. In Table 7, the upstream pressure $Pup\ (bar)$, downstream pressure $Pdn\ (bar)$, and C_V calculated for each valve of the O_2 infrastructure at nominal flowrate is provided.

Table 6 Valve $C_V$value at nominal operating conditions in H_2 infrastructure for each demonstrator

Demo	Equipment	H_2 Flowrate (Nm³/h)	H_2 Flowrate (kg/h)	PCV3			PCV4			PCV5			FCV2		
				P_{up}	P_{dn}	C_V	P_{up}	P_{dn}	C_V	P_{up}	P_{dn}	C_V	P_{up}	P_{dn}	C_V
Demo1	Preheating Station	33	2.99	200	50	0.005	50	15	0.02	15	1.5	0.06	1.5	1	0.83
Demo2	Holding Furnace	1750	157	200	50	0.181	50	15	0.72	15	1.5	2.21	1.5	1.15	32.5

Demo3	Rotary Furnace	267	24	200	50	0.026	50	15	0.10	15	1.5	0.32	1.5	1.15	4.75
Demo4	Reverb Furnace	833	75	200	50	0.082	50	15	0.324	15	1.5	1.52	1.5	1.15	9.09
Demo5	Reverb Furnace	3666	329	200	50	0.363	50	15	1.46	15	1.5	7.04	1.5	1.15	68
Demo6	Artificial Aging Furnace	56.7	5.09	200	50	0.006	50	15	0.023	15	1.5	0.07	1.5	1.15	1.01
Demo7	Tunnel Furnace	800	72	200	50	0.079	50	15	0.319	15	1.5	0.97	1.5	1.15	14.24
Demo8	Walking Beam Furnace	6666.6	599.9	200	50	0.660	50	15	2.655	15	4	8.2	4	3	43.35
Demo9	Walking Beam Furnace	500	45	200	50	0.049	50	15	0.199	15	1.5	0.61	1.5	1	7.83
Demo10	Ladle Preheating	500	45	200	50	0.049	50	15	0.199	15	1.5	0.61	1.5	1.15	8.90
Demo11	Indirect Heating	120	10.8	200	50	0.012	50	15	0.048	15	1.5	0.15	1.5	1.15	2.14
Demo12	Direct Heating	400	36	200	50	0.04	50	15	0.159	15	1.5	0.48	1.5	1.15	7.12

Table 7 Valves $C_V$value at nominal operating conditions in O_2 infrastructure for each demonstrator

Demo	Equipment	O_2 Flowrate (Nm³/h)	O_2 Flowrate (kg/h)	PCV1			PCV2			FCV1		
				P_{up}	P_{dn}	C_V	P_{up}	P_{dn}	C_V	P_{up}	P_{dn}	C_V
Demo1	Preheating Station	15	38	18	15	0.19	15	9	0.16	9	4	0.25
Demo2	Holding Furnace	892	1273	18	15	6.37	15	9	5.58	9	4	15.1
Demo3	Rotary Melting Furnace	136	193	18	15	0.93	15	9	0.81	9	4	1.26
Demo4	Reverb Melting Furnace	425	603	18	15	3.76	15	9	3.29	9	8	8.94
Demo5	Reverb Melting Furnace	1864	2647	18	15	12	15	9	12	9	4	16
Demo6	Artificial Aging Furnace	Only Air will be used in the demonstration										
Demo7	Tunnel Furnace	Only Air will be used in the demonstration										
Demo8	Walking Beam Furnace	3400	4828	18	15	23.24	15	9	20.35	9	3	30.9
Demo9	Walking Beam Furnace	255	362	18	15	1.74	15	9	1.53	9	4	2.37
Demo10	Ladle Preheating	255	362	18	15	1.74	15	9	1.53	9	4	2.37
Demo11	Indirect Heating	61	86	18	15	0.42	15	9	0.37	9	4	0.57
Demo12	Direct Heating	204	289	18	15	1.39	15	9	1.22	9	4	1.89

5.2.2 Valves Opening Results

To simulate the opening of valves under diverse operating conditions, it is imperative to integrate the characteristic curve of the valve into the Aspen Plus model. This valve selection and characteristic curves are chosen through the utilization of a Fisher valve specification manager. The selection process involves identifying a C_V valve with a value at approximately 50% valve opening that aligns with the C_V value calculated at nominal flowrate conditions, which is already tabulated in section 5.2.1.

Furthermore, as a practical guideline, the valve characteristic curve is chosen to ensure that, under off-design conditions, the valve opening remains confined within the 20-90% travel range. The subsequent sub-section presents the characteristic curves chosen for each control valve across all demonstrators, encompassing both the H_2 and O_2 infrastructure.

Notably, these selected valves undergo simulation within Aspen Plus for all demonstrators at load conditions of 75%, 100%, and 125% of the nominal load. The simulations span various H_2 supply pressures, ranging from 200 bar to 25 bar. This comprehensive analysis aims to assess the valve openings at these varied operating conditions, providing insights into the performance and behavior of the valves in response to fluctuations in load and supply pressure.

5.2.2.1 Demo 1

Table 8 provides the control valves size, class, and flow characteristic curve for all the valves of the H_2 and O_2 infrastructure for Demo1 (Preheating Station) demonstrator. The valves flow characteristic curve has been selected from a manufacturer sizing manager. The valve class has been selected based on the upstream pressure and temperature conditions. These characteristic curves have been in inserted in the Aspen Plus model and Table 9 presents the simulation results for the valve opening at different flowrate and different H_2 supply pressures conditions. The maximum results for the valve opening are within 20%-80% range as per the standard practice.

Table 8 Demo1 (Preheating Station): Selected valves size, class, and flow characteristic curve (C_V vs % opening)

Valve Size (in)	1/2	1/2	1/2	1/2	1/2	1/2	1/2
Class	CL150	CL150	CL1500	CL300	CL150	CL150	CL150
Valve Opening	PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	FCV2
10%	0.056	0.056	0.0037	0.0037	0.016	0.056	0.118
20%	0.073	0.073	0.0055	0.0055	0.026	0.073	0.191
30%	0.101	0.101	0.0085	0.0085	0.038	0.101	0.309
40%	0.146	0.146	0.0121	0.0121	0.052	0.146	0.457
50%	0.216	0.216	0.0163	0.0163	0.07	0.216	0.607
60%	0.312	0.312	0.0205	0.0205	0.088	0.312	0.941
70%	0.433	0.433	0.0246	0.0246	0.107	0.433	1.39
80%	0.588	0.588	0.0284	0.0284	0.127	0.588	2
90%	0.802	0.802	0.0326	0.0326	0.153	0.802	2.77
100%	1.07	1.07	0.0389	0.0389	0.181	1.07	3.34

Table 9 Demo1 (Preheating Station): valve % opening results at various operating conditions

H_2 Flowrate (kg/h)	O_2 Flowrate (kg/h)	H_2 supply pressure (bar)	ΔP (PCV3) (bar)	ΔP (PCV4) (bar)	% Opening						
					PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	FCV2
3.6	28.9	200	150	40	38	34	12	47	54	61	55
3.6	28.9	100	50	40	38	38	30	46	54	61	55
3.6	28.9	80	30	40	38	38	38	46	54	61	55
3.6	28.9	50	15	25	38	38	54	71	54	61	55
3.6	28.9	35	15	10	38	38	80	86	54	61	55
4.8	38.6	200	150	40	45	41	20	58	71	69	61
4.8	38.6	100	50	40	45	41	38	58	70	69	61
4.8	38.6	80	30	40	45	41	48	58	70	69	61
4.8	38.6	50	15	25	45	41	74	80	70	69	61
4.8	38.6	35	15	10	45	41	91	85	70	69	61
6	48.2	200	150	40	51	56	25	71	87	77	67
6	48.2	100	50	40	51	56	45	70	87	77	67
6	48.2	80	30	40	51	56	57	70	86	77	67
6	48.2	50	15	25	51	56	90	95	86	77	67

5.2.2.2 Demo 2

Table *10* provides the control valves size, class, and flow characteristic curve for all valves of the H_2 and O_2 infrastructure for Demo2 (Holding Furnace) demonstrator. Table 11 presents the simulation results for the valve opening at different flowrate and different H_2 supply pressures conditions.

Table 10 Demo2 (Holding Furnace): Selected valves size, class, and flow characteristic curve

Valve Size (in)	1	1	1	1	3/4	1	1
Class	CL150	CL150	CL1500	CL300	CL150	CL150	CL150
Valve Opening	PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	FCV2
10%	0.795	0.795	0.118	0.118	0.795	0.795	3.11
20%	1.23	1.23	0.191	0.191	1.23	1.23	5.77
30%	1.91	1.91	0.309	0.309	1.91	1.91	9.12
40%	2.95	2.95	0.457	0.457	2.95	2.95	13.7
50%	4.3	4.3	0.607	0.607	4.3	4.3	21.7
60%	6.46	6.46	0.941	0.941	6.46	6.46	36
70%	9.84	9.84	1.39	1.39	9.84	9.84	60.4
80%	16.4	16.4	2	2	16.4	16.4	86.4
90%	22.2	22.2	2.77	2.77	22.2	22.2	104
100%	28.1	28.1	3.34	3.34	28.1	28.1	114

Table 11 Demo2 (Holding Furnace): Valve % opening results at various operating conditions

H_2 Flowrate (kg/h)	O_2 Flowrate (kg/h)	H_2 supply pressure (bar)	ΔP (PCV3) (bar)	ΔP (PCV4) (bar)	% Opening						
					PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	PCV1
118	992	200	150	40	52	34	12	42	36	59	42
118	992	100	50	40	52	34	28	42	36	59	42
118	992	80	30	40	52	34	35	42	36	59	42
118	992	50	15	25	52	34	52	53	36	59	42
118	992	35	10	15	52	34	60	62	36	59	42
118	992	25	10	5	52	34	65	80	36	59	42
157	1323	200	150	40	59	41	19	52	43	66	48
157	1323	100	50	40	59	41	35	52	43	66	48
157	1323	80	30	40	59	41	43	52	43	66	48
157	1323	50	15	25	59	41	58	60	43	66	48
157	1323	35	20	5	59	41	62	88	43	66	48
157	1323	25	10	5	59	41	73	88	43	66	48
196	1654	200	150	40	64	56	24	57	50	71	52
196	1654	100	50	40	64	56	41	57	50	71	52
196	1654	80	30	40	64	56	51	57	50	71	52
196	1654	50	15	25	64	56	63	65	50	71	52
196	1654	35	10	15	64	56	73	75	50	71	52
196	1654	25	10	5	64	56	79	100	50	71	52

5.2.2.3 Demo 3

Table *12* provides the control valves size, class, and flow characteristic curve for all valves of the H_2 and O_2 infrastructure for Demo3 (Rotary Furnace) demonstrator. Table 13 presents the simulation results for the valve opening at different flowrate and different H_2 supply pressures conditions.

Table 12 Demo3 (Rotary Furnace): Selected valves size, class, and flow characteristic curve

Valve Size (in)	1	1	1	1/2	1/2	1	2
Class	CL150	CL150	CL1500	CL300	CL150	CL150	CL150
Valve Opening	PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	FCV2
10%	0.129	0.129	0.001	0.088	0.088	0.189	0.434
20%	0.199	0.199	0.004	0.124	0.124	0.319	0.683
30%	0.308	0.308	0.028	0.175	0.175	0.492	1
40%	0.448	0.448	0.063	0.236	0.236	0.735	1.49
50%	0.62	0.62	0.105	0.327	0.327	1.08	2.21
60%	0.882	0.882	0.154	0.464	0.464	1.53	3.18
70%	1.29	1.29	0.207	0.641	0.641	2.12	4.61
80%	1.8	1.8	0.265	0.881	0.881	2.99	6.73
90%	2.43	2.43	0.326	1.22	1.22	4.17	8.88
100%	3.07	3.07	0.38	1.52	1.52	4.91	10.2

Table 13 Demo3 (Rotary Furnace): Valve % opening results at various operating conditions

H_2 Flowrate (kg/h)	O_2 Flowrate (kg/h)	H_2 supply pressure (bar)	ΔP (PCV3) (bar)	ΔP (PCV4) (bar)	% Opening						
					PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	PCV1
18	144	200	150	35	53	48	28	8	42	45	64
18	144	100	50	35	53	48	35	8	42	45	64
18	144	80	45	20	53	48	37	16	42	45	64
18	144	50	15	20	53	48	49	16	42	45	64
18	144	35	15	10	53	48	54	35	55	45	64
18	144	30	18	4	53	48	56	54	63	45	64
24	193	200	150	35	61	58	30	13	52	53	72
24	193	100	50	35	61	58	38	13	51	53	72
24	193	80	30	35	61	58	43	13	51	53	72
24	193	50	15	20	61	58	55	25	51	53	72
24	193	35	15	10	61	58	62	44	66	53	72
24	193	30	18	4	61	58	65	63	77	53	72
30	241	200	150	35	67	65	32	21	59	59	77
30	241	100	50	35	67	65	42	20	59	59	77
30	241	80	30	35	67	65	48	20	59	59	77
30	241	50	15	20	67	65	62	32	59	59	77
30	241	35	20	7	67	65	68	59	91	59	77
30	241	30	18	4	67	65	73	70	91	59	77

5.2.2.4 Demo 4

Table *14* provides the control valves size, class, and flow characteristic curve for all valves of the H_2 and O_2 infrastructure for *Demo4 (Reverb Furnace)* demonstrator. Table 15 presents the simulation results for the valve opening at different flowrate and different H_2 supply pressures conditions.

Table 14 Demo4 (Reverb Furnace): Selected valves size, class, and flow characteristic curve

Valve Size (in)	1/2	3/4	1/2	1/2	1/2	1 ½	1 ½
Class	CL150	CL150	CL1500	CL300	CL150	CL150	CL150
Valve Opening	PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	FCV2
10%	0.79	0.373	0.056	0.088	0.193	0.795	0.795
20%	1.25	0.617	0.073	0.124	0.324	1.23	1.23
30%	1.8	0.948	0.101	0.175	0.496	1.91	1.91
40%	2.53	1.44	0.146	0.236	0.737	2.95	2.95
50%	3.63	2.14	0.216	0.327	1.07	4.3	4.3
60%	5.28	3.1	0.312	0.464	1.52	6.46	6.46
70%	7.59	4.43	0.433	0.641	2.13	9.84	9.84
80%	10.7	6.14	0.588	0.881	2.93	16.4	16.4
90%	12.7	7.58	0.802	1.22	3.89	22.2	22.2
100%	13.2	8.35	1.07	1.52	4.52	28.1	28.1

Table 15 Demo4 (Reverb Furnace): Valve % opening results at various operating conditions

H_2 Flowrate (kg/h)	O_2 Flowrate (kg/h)	H_2 supply pressure (bar)	ΔP (PCV3) (bar)	ΔP (PCV4) (bar)	% Opening						
					PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	PCV1
56	452	200	150	42	35	55	17	18	53	54	63
56	452	100	50	42	35	55	38	39	53	54	63
56	452	80	30	42	35	55	45	39	53	54	63
56	452	50	15	27	35	55	59	50	53	54	63
56	452	35	10	17	35	55	71	60	53	54	63
56	452	25	9	8	35	55	78	79	53	54	63
75	603	200	120	72	43	63	26	33	62	61	70
75	603	100	50	42	43	63	45	48	62	61	70
75	603	80	30	42	43	63	53	48	62	61	70
75	603	50	15	27	43	63	68	58	62	61	70
75	603	35	10	17	43	63	80	69	62	61	70
75	603	25	10	7	43	63	87	88	62	61	70
93	754	200	120	72	49	70	32	55	66	66	74
93	754	100	50	42	49	70	51	54	66	66	74
93	754	80	30	42	49	70	59	54	66	66	74
93	754	50	15	27	49	70	75	65	66	66	74
93	754	35	10	17	49	70	87	76	66	66	74
93	754	25	10	7	49	70	96	92	66	66	74

5.2.2.5 Demo 5

Table 16 provides the control valves size, class, and flow characteristic curve for all valves of the H_2 and O_2 infrastructure for Demo5 (Reverb Furnace) demonstrator. Table 17 presents the simulation results for the valve opening at different flowrate and different H_2 supply pressures conditions.

Table 16 Demo5 (Reverb Furnace): Selected valves size, class, and flow characteristic curve

Valve Size (in)	2	2	1	3/4	2	2	3
Class	CL150	CL150	CL1500	CL300	CL150	CL150	CL150
Valve Opening	PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	FCV2
10%	1.65	1.65	0.189	0.373	1.65	1.65	3.11
20%	2.61	2.61	0.319	0.617	2.61	2.61	5.77
30%	4.3	4.3	0.492	0.948	4.3	4.3	9.12
40%	6.62	6.62	0.735	1.44	6.62	6.62	13.7
50%	11.1	11.1	1.08	2.14	11.1	11.1	21.7
60%	20.7	20.7	1.53	3.1	20.7	20.7	36
70%	32.8	32.8	2.12	4.43	32.8	32.8	60.4
80%	44.7	44.7	2.99	6.14	44.7	44.7	86.4
90%	50	50	4.17	7.58	50	50	104
100%	53.8	53.8	4.91	8.35	53.8	53.8	114

Table 17 Demo5 (Reverb Furnace): Valve % opening results at various operating conditions

H_2 Flowrate (kg/h)	O_2 Flowrate (kg/h)	H_2 supply pressure (bar)	ΔP (PCV3) (bar)	ΔP (PCV4) (bar)	% Opening						
					PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	PCV1
245	1985	200	150	40	47	45	17	32	34	51	51
245	1985	100	50	40	47	45	34	31	34	51	51
245	1985	80	30	40	47	45	42	31	34	51	51
245	1985	50	15	25	47	45	56	40	34	51	50
245	1985	35	10	15	47	45	67	49	34	51	50
245	1985	25	10	7	47	45	74	65	39	51	50
329	2647	200	150	40	52	51	39	41	52	56	68
329	2647	100	50	40	52	51	38	41	51	56	68
329	2647	80	30	40	52	51	38	41	51	56	68
329	2647	50	15	25	52	51	48	41	51	56	68
329	2647	35	10	15	52	51	57	41	66	56	68
329	2647	25	10	7	52	51	73	46	77	56	68
411	3308	200	150	40	55	57	29	44	46	60	85
411	3308	100	50	40	55	57	47	44	46	60	85
411	3308	80	30	40	55	57	56	44	46	60	85
411	3308	50	15	25	55	57	72	53	46	60	85
411	3308	35	10	15	55	57	82	63	46	60	84
411	3308	25	10	7	55	57	89	81	51	60	85

5.2.2.6 Demo 6

Table *18* provides the control valves size, class, and flow characteristic curve for all valves of the H_2 and O_2 infrastructure for Demo6 (Artificial Aging Furnace) demonstrator. Table 19 presents the simulation results for the valve opening at different flowrate and different H_2 supply pressures conditions.

Table 18 Demo6 (Artificial Aging Furnace): Valves size, class, and flow characteristic curve

Valve Size (in)	1/2	1/2	1/2	1/2	1/2	1/2	1/2
Class	CL150	CL150	CL1500	CL300	CL150	CL150	CL150
Valve Opening	PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	FCV2
10%	-	-	0.0037	0.0356	0.016	-	0.118
20%	-	-	0.0055	0.0524	0.026	-	0.191
30%	-	-	0.0085	0.0736	0.038	-	0.309
40%	-	-	0.0121	0.0984	0.052	-	0.457
50%	-	-	0.0163	0.127	0.07	-	0.607
60%	-	-	0.0205	0.158	0.088	-	0.941
70%	-	-	0.0246	0.191	0.107	-	1.39
80%	-	-	0.0284	0.224	0.127	-	2
90%	-	-	0.0326	0.257	0.153	-	2.77
100%	-	-	0.0389	0.294	0.181	-	3.34

Table 19 Demo6 (Artificial Aging Furnace): Valve % opening results at various operating conditions

H_2 Flowrate (kg/h)	O_2 Flowrate (kg/h)	H_2 supply pressure (bar)	ΔP (PCV3) (bar)	ΔP (PCV4) (bar)	% Opening						
					PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	PCV1
3.8	-	200	150	35	-	-	14	49	41	-	56
3.8	-	100	50	35	-	-	32	49	40	-	56
3.8	-	80	30	35	-	-	40	49	40	-	56
3.8	-	50	15	20	-	-	61	67	40	-	56
3.8	-	35	13	14	-	-	78	97	70	-	56
5	-	200	150	35	-	-	21	61	51	-	62
5	-	100	50	35	-	-	40	61	50	-	62
5	-	80	30	35	-	-	49	61	50	-	62
5	-	50	15	20	-	-	77	86	50	-	62
5	-	35	15	10	-	-	94	75	73	-	62
6.3	-	200	150	35	-	-	26	75	62	-	68
6.3	-	100	50	35	-	-	47	75	62	-	68
6.3	-	80	30	35	-	-	59	74	62	-	68
6.3	-	50	13	22	-	-	96	97	62	-	68
6.3	-	35	15	15	-	-	96	84	90	-	68

5.2.2.7 Demo 7

Table 20 provides the control valves size, class, and flow characteristic curve for all valves of the H_2 and O_2 infrastructure for Demo7 (Tunnel Furnace) demonstrator. Since Demo7 will be performing demonstration with H_2/Air burners, only H_2 valves data is provided below. Table 21 presents the simulation results for the valve opening at different flowrate and different H_2 supply pressures conditions.

Table 20 Demo7 (Tunnel Furnace) Selected valves size, class, and flow characteristic curve

Valve Size (in)	-	-	1	1	1	-	1 ½
Class	CL150	CL150	CL1500	CL300	CL150	CL150	CL150
Valve Opening	PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	FCV2
10%	-	-	0.016	0.088	0.189	-	0.795
20%	-	-	0.026	0.124	0.319	-	1.23
30%	-	-	0.038	0.175	0.492	-	1.91
40%	-	-	0.052	0.236	0.735	-	2.95
50%	-	-	0.07	0.327	1.08	-	4.3
60%	-	-	0.088	0.464	1.53	-	6.46
70%	-	-	0.107	0.641	2.12	-	9.84
80%	-	-	0.127	0.881	2.99	-	16.4
90%	-	-	0.153	1.22	4.17	-	22.2
100%	-	-	0.181	1.52	4.91	-	28.1

Table 21 Demo7 (Tunnel Furnace) valve % opening results at various operating conditions

H_2 Flowrate (kg/h)	O_2 Flowrate (kg/h)	H_2 supply pressure (bar)	ΔP (PCV3) (bar)	ΔP (PCV4) (bar)	% Opening						
					PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	PCV1
54	-	200	150	40	-	-	13	38	51	-	63
54	-	100	50	40	-	-	37	38	51	-	63
54	-	80	30	40	-	-	44	38	51	-	63
54	-	50	15	25	-	-	58	49	51	-	63
54	-	35	10	15	-	-	70	60	51	-	63
54	-	25	9	6	-	-	78	78	51	-	63
72	-	200	150	40	-	-	24	47	61	-	70
72	-	100	50	40	-	-	44	47	61	-	70
72	-	80	30	40	-	-	52	47	61	-	70
72	-	50	15	25	-	-	67	58	61	-	70
72	-	35	10	15	-	-	79	69	61	-	70
72	-	25	10	5	-	-	86	90	61	-	70
90	-	200	150	40	-	-	31	54	69	-	74
90	-	100	50	40	-	-	50	54	69	-	74
90	-	80	30	40	-	-	58	53	69	-	74
90	-	50	15	25	-	-	74	64	69	-	74
90	-	35	10	15	-	-	86	76	69	-	74
90	-	25	150	40	-	-	96	91	69	-	74

5.2.2.8 Demo 8

Table 22 provides the control valves size, class, and flow characteristic curve for all valves of the H_2 and O_2 infrastructure for Demo8 (Walking Beam Furnace) demonstrator. Table 23 presents the simulation results for the valve opening at different flowrate and different H_2 supply pressures conditions.

Table 22 Demo8 (Walking Beam Furnace): Valves size, class, and flow characteristic curve

Valve Size (in)	3	3	3/4	1	2	3	3
Class	CL150	CL150	CL1500	CL300	CL150	CL150	CL150
Valve Opening	PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	FCV2
10%	3.11	3.11	0.373	0.79	1.65	3.11	3.11
20%	5.77	5.77	0.617	1.25	2.61	5.77	5.77
30%	9.12	9.12	0.948	1.8	4.3	9.12	9.12
40%	13.7	13.7	1.44	2.53	6.62	13.7	13.7
50%	21.7	21.7	2.14	3.63	11.1	21.7	21.7
60%	36	36	3.1	5.28	20.7	36	36
70%	60.4	60.4	4.43	7.59	32.8	60.4	60.4
80%	86.4	86.4	6.14	10.7	44.7	86.4	86.4
90%	104	104	7.58	12.7	50	104	104
100%	114	114	8.35	13.2	53.8	114	114

Table 23 Demo8 (Walking Beam Furnace): Valve % opening results at various operating conditions

H_2 Flowrate (kg/h)	O_2 Flowrate (kg/h)	H_2 supply pressure (bar)	ΔP (PCV3) (bar)	ΔP (PCV4) (bar)	% Opening						
					PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	PCV1
450	3621	200	150	35	45	42	16	33	40	50	58
450	3621	100	50	35	45	42	33	33	40	50	58
450	3621	80	30	35	45	42	40	33	40	50	58
450	3621	50	25	15	45	42	50	53	49	50	58
450	3621	35	20	7	45	42	58	68	53	50	58
450	3621	25	10	7	45	42	70	68	53	50	58
599	2647	200	150	35	51	49	23	42	46	56	63
599	2647	100	50	35	51	49	40	42	46	56	63
599	2647	80	30	35	51	49	47	42	46	56	63
599	2647	50	25	15	51	49	57	61	54	56	63
599	2647	35	20	7	51	49	66	76	58	56	63
599	2647	25	10	7	51	49	79	76	58	56	63
750	3308	200	150	35	55	54	28	48	50	60	67
750	3308	100	50	35	55	54	45	48	50	60	67
750	3308	80	30	35	55	54	53	48	50	60	67
750	3308	50	25	15	55	54	64	67	57	60	67
750	3308	35	20	7	55	54	73	84	63	60	67
750	3308	25	10	7	55	54	89	84	63	60	67

5.2.2.9 Demo 9

Table 24 provides the control valves size, class, and flow characteristic curve for all valves of the H_2 and O_2 infrastructure for Demo9 (Walking Beam Furnace) demonstrator. Table 25 presents the simulation results for the valve opening at different flowrate and different H_2 supply pressures conditions.

Table 24 Demo9 (Walking Beam Furnace): Valves size, class, and flow characteristic curve

Valve Size (in)	1	1	1	1/2	3/4	1	1
Class	CL150	CL150	CL1500	CL300	CL150	CL150	CL150
Valve Opening	PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	FCV2
10%	0.374	0.374	0.001	0.134	0.128	0.374	0.783
20%	0.622	0.622	0.005	0.202	0.206	0.622	1.29
30%	0.965	0.965	0.03	0.313	0.325	0.965	1.86
40%	1.47	1.47	0.068	0.448	0.479	1.47	2.71
50%	2.17	2.17	0.115	0.613	0.629	2.17	4.18
60%	3.15	3.15	0.169	0.879	0.984	3.15	6.44
70%	4.57	4.57	0.229	1.27	1.46	4.57	9.54
80%	6.52	6.52	0.294	1.77	2.14	6.52	13.1
90%	8.17	8.17	0.364	2.47	3.06	8.17	15.7
100%	8.84	8.84	0.437	3	3.75	8.84	17.4

Table 25 Demo9 (Walking Beam Furnace): Valve % opening results at various operating conditions

H_2 Flowrate (kg/h)	O_2 Flowrate (kg/h)	H_2 supply pressure (bar)	ΔP (PCV3) (bar)	ΔP (PCV4) (bar)	% Opening						
					PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	PCV1
33.7	271.5	200	150	40	37	34	33	11	54	59	51
33.7	271.5	100	50	40	37	34	43	10	54	59	51
33.7	271.5	80	30	40	37	34	49	10	54	59	51
33.7	271.5	50	30	10	37	34	57	35	54	59	51
33.7	271.5	35	10	15	37	34	76	28	54	59	51
33.7	271.5	25	13	4	37	34	83	54	59	59	51
45	362	200	150	40	44	42	36	18	61	66	58
45	362	100	50	40	44	42	48	18	61	66	58
45	362	80	30	40	44	42	56	18	61	66	58
45	362	50	30	10	44	42	66	44	61	66	58
45	362	35	10	15	44	42	89	35	61	66	58
45	362	25	13	4	44	42	97	62	69	66	58
56	452.6	200	150	40	50	50	23	69	23	72	63
56	452.6	100	50	40	50	50	23	69	23	72	63
56	452.6	80	30	40	50	50	23	69	23	72	63
56	452.6	50	30	10	50	50	51	68	51	72	63
56	452.6	35	15	10	50	50	51	68	51	72	63
56	452.6	25	20	3	50	50	75	88	75	72	63

5.2.2.10 Demo 10

Table *26* provides the control valves size, class, and flow characteristic curve for all valves of the H_2 and O_2 infrastructure for Demo10 (Ladle Preheating) demonstrator. Table *27* presents the simulation results for the valve opening at different flowrate and different H_2 supply pressures conditions.

Table 26 Demo10 (Ladle Preheating): Selected valves size, class, and flow characteristic curve

Valve Size (in)	1	1	1	1/2	3/4	1	1
Class	CL150	CL150	CL1500	CL300	CL150	CL150	CL150
Valve Opening	PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	FCV2
10%	0.374	0.374	0.001	0.134	0.128	0.374	0.783
20%	0.622	0.622	0.005	0.202	0.206	0.622	1.29
30%	0.965	0.965	0.03	0.313	0.325	0.965	1.86
40%	1.47	1.47	0.068	0.448	0.479	1.47	2.71
50%	2.17	2.17	0.115	0.613	0.629	2.17	4.18
60%	3.15	3.15	0.169	0.879	0.984	3.15	6.44
70%	4.57	4.57	0.229	1.27	1.46	4.57	9.54
80%	6.52	6.52	0.294	1.77	2.14	6.52	13.1
90%	8.17	8.17	0.364	2.47	3.06	8.17	15.7
100%	8.84	8.84	0.437	3	3.75	8.84	17.4

Table 27 Demo10 (Ladle Preheating Furnace): Valve % opening results at various operating conditions

H_2 Flowrate (kg/h)	O_2 Flowrate (kg/h)	H_2 supply pressure (bar)	ΔP (PCV3) (bar)	ΔP (PCV4) (bar)	% Opening						
					PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	PCV1
33.7	271	200	150	40	37	34	33	11	54	59	51
33.7	271	100	50	40	37	34	43	10	54	59	51
33.7	271	80	30	40	37	34	49	10	54	59	51
33.7	271	50	30	10	37	34	57	35	54	59	51
33.7	271	35	10	15	37	34	76	28	54	59	51
33.7	271	25	13	4	37	34	83	54	59	59	51
45	362	200	150	40	44	42	36	18	61	66	58
45	362	100	50	40	44	42	48	18	61	66	58
45	362	80	30	40	44	42	56	18	61	66	58
45	362	50	30	10	44	42	66	44	61	66	58
45	362	35	10	15	44	42	89	35	61	66	58
45	362	25	13	4	44	42	97	62	69	66	58
56	452.6	200	150	40	50	50	23	69	23	72	63
56	452.6	100	50	40	50	50	23	69	23	72	63
56	452.6	80	30	40	50	50	23	69	23	72	63
56	452.6	50	30	10	50	50	51	68	51	72	63
56	452.6	35	15	10	50	50	51	68	51	72	63
56	452.6	25	20	3	50	50	75	88	75	72	63

5.2.2.11 Demo 11

Table *28* provides the control valves size, class, and flow characteristic curve for all valves of the H_2 and O_2 infrastructure for Demo11 (Annealing Furnace) demonstrator. Table *29* presents the simulation results for the valve opening at different flowrate and different H_2 supply pressures conditions.

Table 28 Demo11 (Annealing Furnace): Selected Valves size, class, and flow characteristic curve)

Valve Size (in)	1/2	1/2	1	1/2	1/2	1/2	3/4
Class	CL150	CL150	CL1500	CL300	CL150	CL150	CL150
Valve Opening	PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	FCV2
10%	0.088	0.088	0.001	0.016	0.118	0.088	0.154
20%	0.124	0.124	0.002	0.026	0.191	0.124	0.192
30%	0.175	0.175	0.013	0.038	0.309	0.175	0.311
40%	0.236	0.236	0.029	0.052	0.457	0.236	0.505
50%	0.327	0.327	0.049	0.07	0.607	0.327	0.763
60%	0.464	0.464	0.072	0.088	0.941	0.464	1.18
70%	0.641	0.641	0.097	0.107	1.39	0.641	1.91
80%	0.881	0.881	0.124	0.127	2	0.881	3.05
90%	1.22	1.22	0.154	0.153	2.77	1.22	4.93
100%	1.52	1.52	0.18	0.181	3.34	1.52	6.41

Table 29 Demo11 (Annealing Furnace): Valve % opening results at various operating conditions

H_2 Flowrate (kg/h)	O_2 Flowrate (kg/h)	H_2 supply pressure (bar)	ΔP (PCV3) (bar)	ΔP (PCV4) (bar)	% Opening						
					PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	PCV1
8	65	200	150	42	48	42	18	26	21	56	67
8	65	100	50	42	48	42	24	26	21	56	67
8	65	80	30	42	48	42	28	26	21	56	67
8	65	50	15	27	48	42	38	37	21	56	67
8	65	35	10	17	48	42	46	48	21	56	67
8	65	25	10	11	48	42	53	71	38	56	67
10.8	86	200	150	42	57	51	20	35	28	64	73
10.8	86	100	50	42	57	51	28	35	27	64	73
10.8	86	80	30	42	57	51	33	35	27	64	73
10.8	86	50	15	27	57	51	45	46	27	64	73
10.8	86	35	10	17	57	51	55	61	27	64	73
10.8	86	25	10	11	57	51	64	88	48	64	73
13	108	200	150	42	63	57	21	41	32	71	78
13	108	100	50	42	63	57	31	41	32	71	78
13	108	80	30	42	63	57	37	41	32	71	78
13	108	50	15	27	63	57	50	53	32	71	78
13	108	35	10	17	63	57	62	71	32	71	78
13	108	25	10	11	63	57	72	99	53	71	78

5.2.2.12 Demo 12

Table 30 provides the control valves size, class, and flow characteristic curve for all valves of the H_2 and O_2 infrastructure for Demo12 (Direct Heating Furnace) demonstrator. Table 31 presents the simulation results for the valve opening at different flowrate and different H_2 supply pressures conditions.

Table 30 Demo12 (Direct Heating Furnace): Selected valves size, class, and flow characteristic curve

Valve Size (in)	1	1	1	1/2	3/4	1	1
Class	CL150	CL150	CL1500	CL300	CL150	CL150	CL150
Valve Opening	PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	FCV2
10%	0.374	0.374	0.001	0.134	0.128	0.374	0.783
20%	0.622	0.622	0.005	0.202	0.206	0.622	1.29
30%	0.965	0.965	0.03	0.313	0.325	0.965	1.86
40%	1.47	1.47	0.068	0.448	0.479	1.47	2.71
50%	2.17	2.17	0.115	0.613	0.629	2.17	4.18
60%	3.15	3.15	0.169	0.879	0.984	3.15	6.44
70%	4.57	4.57	0.229	1.27	1.46	4.57	9.54
80%	6.52	6.52	0.294	1.77	2.14	6.52	13.1
90%	8.17	8.17	0.364	2.47	3.06	8.17	15.7
100%	8.84	8.84	0.437	3	3.75	8.84	17.4

Table 31 Demo12 (Direct Heating Furnace): Valve % opening results at various operating conditions

H_2 Flowrate (kg/h)	O_2 Flowrate (kg/h)	H_2 supply pressure (bar)	ΔP (PCV3) (bar)	ΔP (PCV4) (bar)	% Opening						
					PCV1	PCV2	PCV3	PCV4	PCV5	FCV1	PCV1
27	217	200	150	40	31	28	30	8	46	53	46
27	217	100	50	40	31	28	39	8	46	53	46
27	217	80	30	40	31	28	44	8	46	53	46
27	217	50	15	25	31	28	56	14	45	53	46
27	217	35	10	17	31	28	68	22	53	53	46
27	217	25	10	11	31	28	76	34	73	53	46
36	289	200	150	40	38	35	33	12	54	60	53
36	289	100	50	40	38	35	44	12	54	60	53
36	289	80	30	40	38	35	50	12	54	60	53
36	289	50	15	25	38	35	65	21	54	60	53
36	289	35	10	17	38	35	79	29	59	60	53
36	289	25	10	11	38	35	89	43	83	60	53
45	362	200	150	40	44	42	36	18	59	66	58
45	362	100	50	40	44	42	48	18	59	66	58
45	362	80	30	40	44	42	56	18	59	66	58
45	362	50	15	25	44	42	73	26	59	66	58
45	362	35	10	17	44	42	89	35	65	66	58
45	362	25	15	6	44	42	96	62	95	66	58

6 Conclusions

The key findings of the process simulations conducted in Aspen Plus for H_2 and O_2 infrastructure, which involved the sizing and operation of pipelines and control valves, are as follows.

1. The transport of H_2 within pipelines can attain higher velocities, reaching up to 60 m/s, thanks to its lower density, thereby minimizing hydraulic losses. In contrast, the conventional upper limit for natural gas velocity in pipelines typically hovers below 20 m/s.
2. When it comes to transporting O_2 within pipelines, it is crucial to adhere to an upper velocity limit of approximately 15 m/s, as surpassing this threshold can lead to undesirable high hydraulic losses.
3. Adhering to standard industrial practices, the H_2 infrastructure recommends installing a maximum of two Pressure Reduction Valves in the primary letdown (decompression station). This primary letdown effectively reduces pressure from 200 barg to approximately 10 barg.
4. In the secondary letdown, it is advisable to implement only one pressure reduction stage for H_2, where the pressure is further reduced to typically less than 500 mbarg, aligning with the precise burner specifications.
5. Similarly, within the O_2 infrastructure, it is recommended to employ a single Pressure Reduction Valve for pressure letdown, ensuring alignment with the final requirements of the burner.
6. In both H_2 and O_2 systems, the incorporation of a dedicated Flow Control Valve is typically imperative to regulate the flow and meet the specific process heating requirements.
7. It is advisable to ensure that the nominal operating conditions are achieved with control valve openings close to 50%. This provides a substantial margin for effectively managing plant requirements even under off-design conditions.
8. When sizing control valves, a pivotal consideration is designing them to meet minimum and maximum flow conditions within valve opening range, spanning from 10% to 90%. This approach ensures optimal control at off-design operational scenarios.
9. The minimum pressure that can be achieved within H_2 tube trailer ranges from 25-35 bars with current configuration. Below this pressure, the pressure control valves are wide open and hence can no longer maintain the pressures at desired setpoint.

7 References

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