A DISTRIBUTED CONTROL SYSTEM DESIGN FOR NUCLEAR-BASED HYDROGEN PRODUCTION WITH COPPER-CHLORINE THERMOCHEMICAL CYCLE

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Abstract

Nuclear-based hydrogen generation is a promising method of large-scale hydrogen production. In a copper-chlorine (Cu-Cl) thermochemical cycle, water is decomposed into hydrogen and oxygen through intermediate copper and chlorine compounds. In this paper, the design of a Distrusted Control System (DCS) for the Cu-Cl cycle is presented. The architecture, communication network and network protocols for the DCS are proposed. A hydrogen reactor unit is used as a case study to demonstrate the detailed design. The configuration of sensors, actuators and controllers is discussed by a Piping & Instrumentation Diagram (P&ID) for the reactor unit.

1. Introduction

Hydrogen is a promising energy carrier that is suitable for use by various industry sectors, ranging from automotive to aircraft industries. As the demand for its usage increases, methods for large-scale hydrogen production have been extensively investigated by various organizations worldwide. Some current means of large-scale hydrogen production include Steam Methane Reforming (SMR), Sulfur-Iodine (S-I) and Calcium-Bromine-Iron (UT-3) thermochemical cycles [1]. Another promising method is through the copper-chlorine (Cu-Cl) thermochemical cycle.

A collaborative effort by Atomic Energy of Canada Limited (AECL), Argonne National Laboratories (ANL), University of Ontario Institute of Technology (UOIT) and other partners has taken place to investigate this potential hydrogen production method. The cycle decomposes water into hydrogen and oxygen through intermediate copper and chlorine compounds with a highest heat temperature input of 530 ˚C [2]. The low input temperature requirement makes the cycle more advantageous over other cycles, especially since it allows the hydrogen production plant to be linked with a wider range of Nuclear Power Plant (NPP) choices. Canada’s Generation IV, Super Critical Water Reactor (SCWR) has been proposed as a suitable source for supplying heat to drive the Cu-Cl thermochemical cycle [2].

As research continues to design and improve the performance of Cu-Cl thermochemical cycle, a major part which must be accounted for is the control of the overall hydrogen production plant to ensure safe and reliable operation. In this paper, a preliminary design of a Distrusted Control System (DCS) is proposed for the Cu-Cl cycle that is currently under research and development. In a DCS, control elements are not central in location but distributed throughout the process. The distributed controllers are connected by a network for the purpose of communication and monitoring. This control methodology was found very efficient and is currently used in many applications that include: factories, hydraulic and thermal power plants, and aerospace industry [3].

This paper is organized as follows: in Section 2, a description of the Cu-Cl cycle is provided. In Section 3, a DCS design is proposed for the overall cycle. In Section 4, the hydrogen reactor unit is used as a case study to demonstrate the detailed design of the DCS. The conclusion is provided in Section 5.

2. Copper-chlorine thermochemical cycle

A conceptual layout of the Cu-Cl cycle used for hydrogen production is presented in Fig. 1. The main components of this cycle are the five interconnected reaction steps with intermediate heat exchangers. Five reactions take place in the cycle according to those recorded in Table 1 [2]. Each reaction step is achieved in a reactor unit.

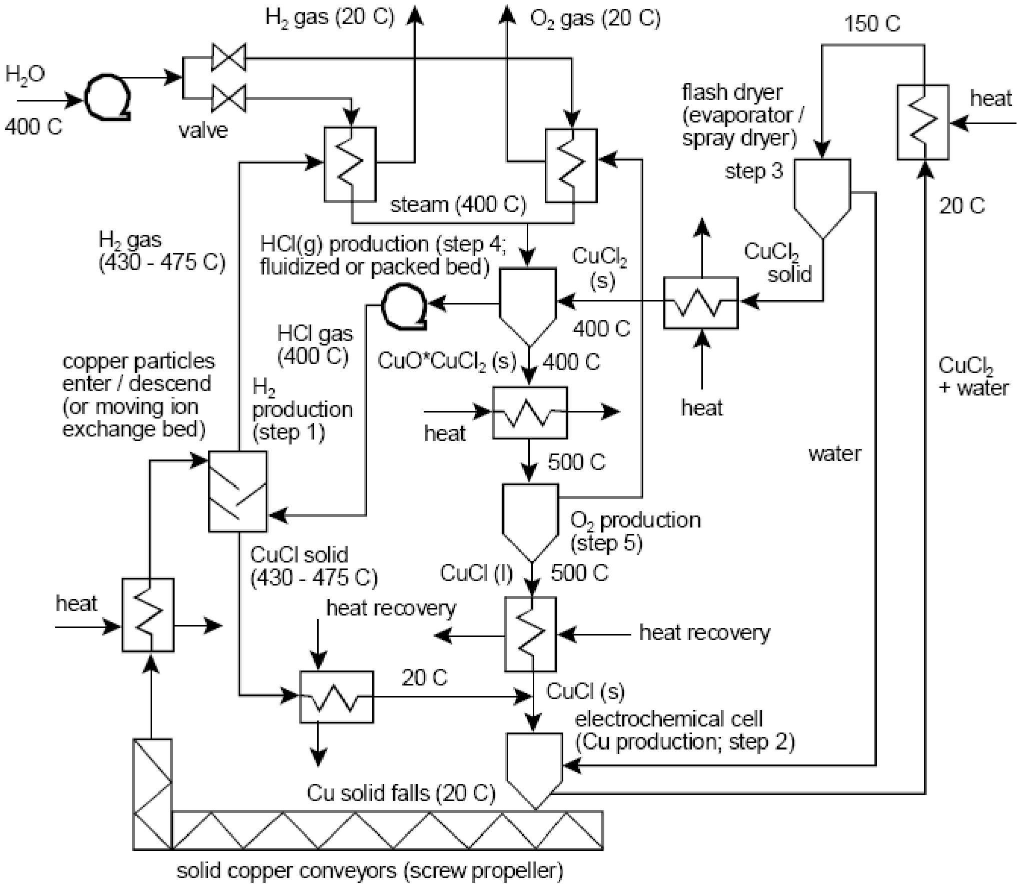

Fig. 1 Conceptual layout of copper-chlorine cycle [2]

Table 1 Reaction steps in the copper-chlorine thermochemical cycle

Step	Reaction	Temperature Range (˚C)
1	$2Cu\ (s) + 2HCl\ (g) \rightarrow 2CuCl\ (l) + H_2\ (g)$	430-475
2	$2CuCl\ (s) \rightarrow 2CuCl\ (aq) \rightarrow CuCl_2\ (aq) + Cu\ (s)$	Ambient (electrolysis)
3	$CuCl_2\ (aq) \rightarrow CuCl_2\ (s)$	<100
4	$2CuCl_2\ (s) + H_2O\ (g) \rightarrow CuO{*}CuCl_2\ (s) + 2HCl\ (g)$	400
5	$CuO{*}CuCl_2\ (s) \rightarrow 2CuCl\ (l) + 1/2O_2\ (g)$	500

In Figure 1, heat input is used to dissociate water into hydrogen and oxygen through the five reaction steps. In the hydrogen reactor unit (Step 1), solid copper particles and HCl gas are used to produce liquid CuCl and hydrogen gas. The liquid CuCl product from Step 1 and Step 5 reactor units is quenched prior to entering an electrochemical cell (Step 2) to produce aqueous $CuCl_2$ and solid copper particles. The copper particles are collected and transported to the hydrogen reactor. The aqueous $CuCl_2$ product is dried in a flash dryer unit (Step 3) before it enters a fluidized bed (Step 4). In the fluidized bed, the solid $CuCl_2$ reacts with high temperature steam to produce solid $CuO{*}CuCl_2$ and HCl gas. The HCl gas is supplied to the hydrogen reactor unit and the $CuO{*}CuCl_2$ is supplied to the oxygen reactor unit (Step 5). In the oxygen reactor unit, the $CuO{*}CuCl_2$ is used to produce liquid CuCl and oxygen gas.

3. Distributed control system design

A preliminary design of a DCS for the nuclear-based Cu-Cl cycle based on Fig. 1 is proposed in this section. The architecture, communication network and network protocols are discussed.

3.1 Architecture of the distributed control system

In a DCS, the control and monitor architecture can be formed by one Plant Display System (PDS) and several partitions [4]. Each partition is composed of one group controller and several device controllers. Partitions can communicate with each other, as well as with the PDS through communication networks. The design of the DCS for the nuclear-based hydrogen production plant is based on a functional distribution scheme where the control application is divided into logical chuncks assigned to different partitions. The architecture of the proposed DCS is presented in Fig. 2. There are five partitions. Each partition is responsible for the control and monitoring of one of the five reaction units in Fig. 1. Within each partition, the group controller communicates with its field controllers through a field network. The characteristics of the blocks in Fig. 2 are explained as follows:

- The PDS allows user intervention through a Human Machine Interface (HMI) system capable of displaying alarms and transients of the systems. It also allows the operators to provide setpoints and control commands.

- The group controllers are responsible to provide complex logic and control of device controllers in respective reactor units. Each group controller communicates with the other group controllers to send/receive feedback. They also communicate with the PDS. The communication is made possible through communication links and network protocols. Furthermore, the group controllers are responsible for independent control of their respective processes in the case of a communication failure.

- The device controllers are responsible for executing simple logic and control of devices in the reactor units, such as motors, valves, and pumps, etc. Each device controller communicates with the other device controllers within the same partition to receive setpoints and feedback that are necessary in making control decisions. The device controllers also receive instructions from the group controller through communication links.

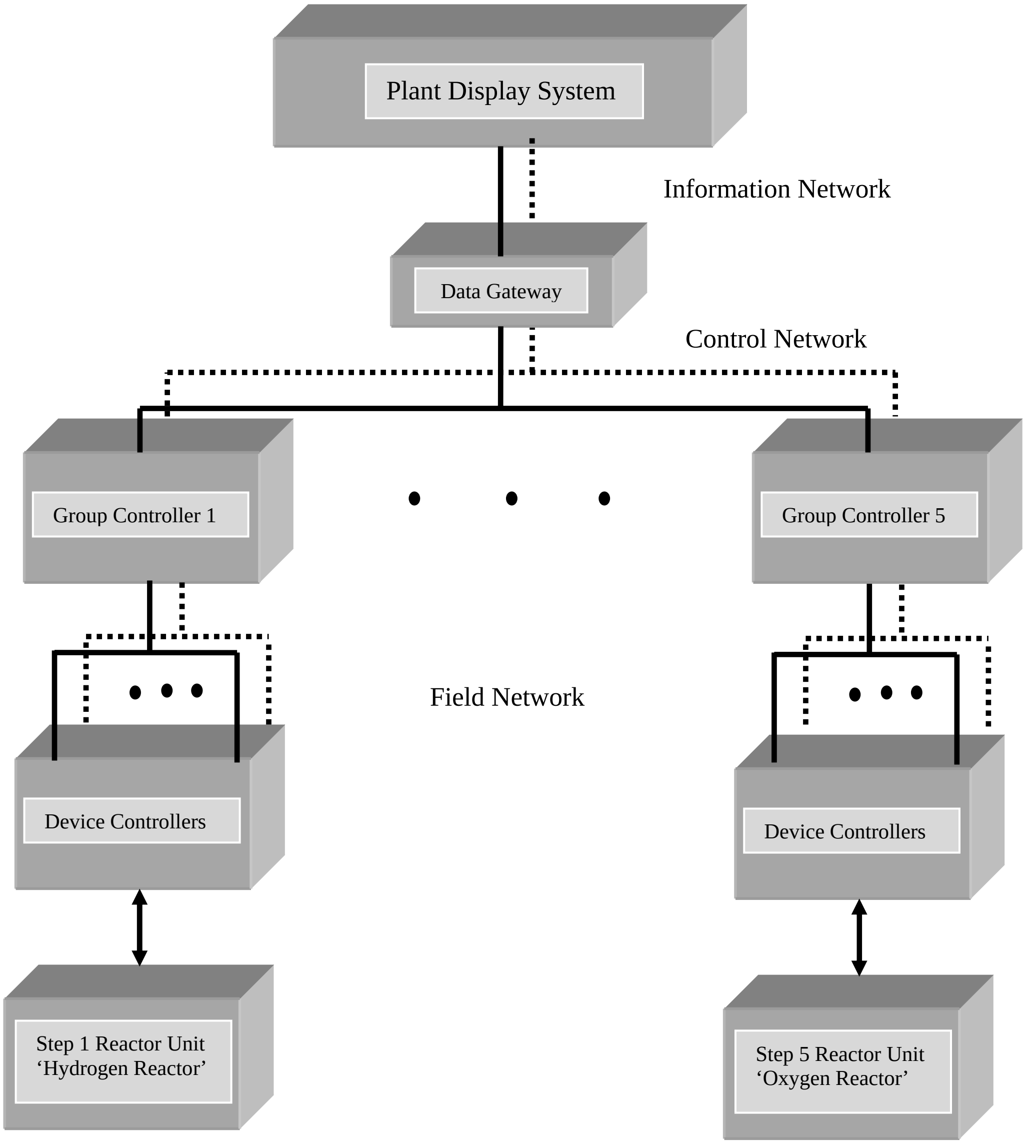

Fig. 2 Architecture of the proposed DCS for Cu-Cl thermochemical cycle

3.2 Communication networks for the proposed distributed control system

The communication in a DCS allows the exchange of information between controllers and with the PDS to provide a safe, controllable, and reliable process operation. According to IEEE Std. 4-4.3.4, communication independence and electrical isolation must be made in safety systems of nuclear power generating stations. Similar requirements are accounted for in the design of the communication networks in the nuclear-based hydrogen production plant.

As shown in Fig. 2, the network in the proposed DCS for the hydrogen production plant has three levels: information network, control network and field network. The information network allows the exchange of data between the PDS and group controllers through a data gateway that supports the communication interface between two different communication protocols. The control network allows the exchange of data between each of the group controllers. The field network allows the exchange of data between each of the device controllers, or between the device controllers and their respective group controller. Moreover, redundancy in information, control and field networks is proposed to ensure a reliable control system.

The information network that is responsible for exchange of data among operator stations as well as with the control network, through a data gateway, is considered a non-safety system. TCP/IP or UDP/IP network protocols can be used to implement the communication mechanism. Communication independence should be provided between non-safety systems, such as the information network, and safety systems, such as the control network. Therefore, a data gateway is used for data transmission between the information network and control network to prevent potential faults in the information network from affecting the control network.

High reliability, maintainability and data transmission speed are very important requirements which the control network must satisfy. Many network protocols were considered in literature for the design of the control network, such as Fiber-channel, ATM, FDDI, SCRAMNet, and Multi-bus. However, each of the protocols either has low speed, low maintainability, or has limitations in terms of independence [5], [6]. Therefore, for the design of the control network in this application, a fast Ethernet based technology, Gigabit Ethernet, is utilized to meet the requirements mentioned above. Many networks based on fast Ethernet protocol were proposed in the literature to specifically meet the hard real-time requirements of NPPs. For example, the use of a Control Network Interface Card (CNIC) based on the microprocessor MPC8260 with fast Ethernet controller was proposed in [5]. A new high-speed real-time network called Plant Instrumentation and Control Network+ (PICNET+) was suggested in [7]. Moreover, a network called Ethernet based Real-Time Control Network (ERCNet) which uses ring topology, token passing mechanism and physical media of fast Ethernet was proposed in [8].

Through the field network, the device controllers can communicate with each other and with the group controller to exchange instructions and data. In this research, RS-585 is proposed as a physical connection layer. It employs HDLC (High-level Data Link Layer) as its data link layer, similar to what has been proposed in [5].

4. Case study: hydrogen reactor unit (Step 1)

Each of the reactions in Table 1 is achieved in a reactor unit that typically consists of various auxiliary systems. In this paper, the hydrogen reactor unit (step 1 in Table 1) is used as an example to demonstrate the detailed design of the proposed DCS. Similar technique can be used for the other four reaction units to implement a complete design of the DCS for the overall hydrogen production plant. Figure 3 shows a possible layout for the auxiliary equipment associated with the hydrogen reactor unit [9]. This schematic sets the foundation for the developments in this section.

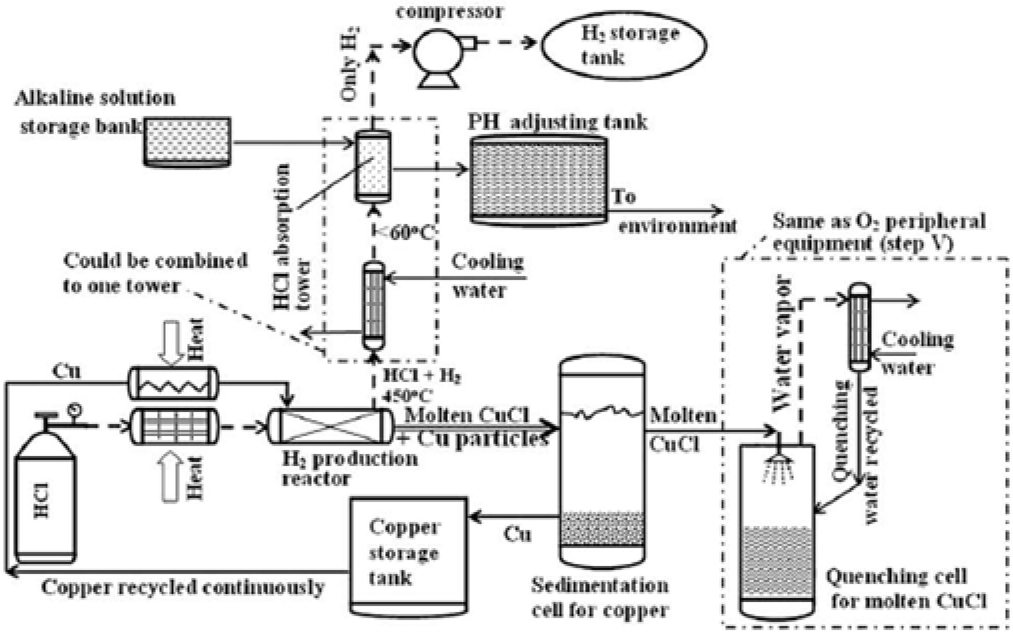

Fig. 3 Auxiliary equipment for the hydrogen reactor unit [9]

4.1 P&ID for the hydrogen reactor unit

From the process control point of view, it is a necessity to implement a P&ID in the design stage of control systems for a particular process plant. A preliminary P&ID for the hydrogen reactor unit is created based on the schematic of Fig 3. This P&ID is decomposed into three parts, as shown in Figures 4, 5 and 6. It is assumed that all motors, pumps, compressors, valves, heat chambers, and heat exchangers are governed by their respective controllers.

In part 1 of the P&ID, as shown in Fig. 4, Line 1-1 assumes an HCl gas feed from Step 4 reaction unit. Four flow measurements, F1-1 to F1-4 provide the flow rate of the HCl gas before and after the two valves, V1-1 and V1-2. Based on those measurements data, the valves control the amount of HCl gas into the heating chamber. The exit stream flow of the heating chamber feeds the hydrogen production reactor with HCl gas at 400 ˚C. Its flow is controlled by V1-4 and P1-1 with V1-3 and P1-2 on standby. Temperature measurements, T1-1 and T1-2, are used by the controller of the heating chamber in order to ensure that the exit stream temperature is 400 ˚C. Line 1-7 provides copper particles to the hydrogen production reactor from a copper storage tank

[9]. The particles are transported using a conveyor whose speed is controlled by M1-2. Since the copper particles should be heated to 80 ˚C before entering the hydrogen production reactor, temperature sensors, T1-3 and T1-4, are used to provide the necessary measurements. Line 1-3 passes cooling water through the hydrogen production reactor. Flow measurements, F1-11 to F1-20, are used by the controllers of the valves and pumps along Lines 1-2 and 1-3 to control the water flow. The hydrogen production reactor delivers molten Cu-Cl and copper particles through Line 1-13 and HCl and H_2 gases through Line 1-12. The production speed is controlled by M1-1.

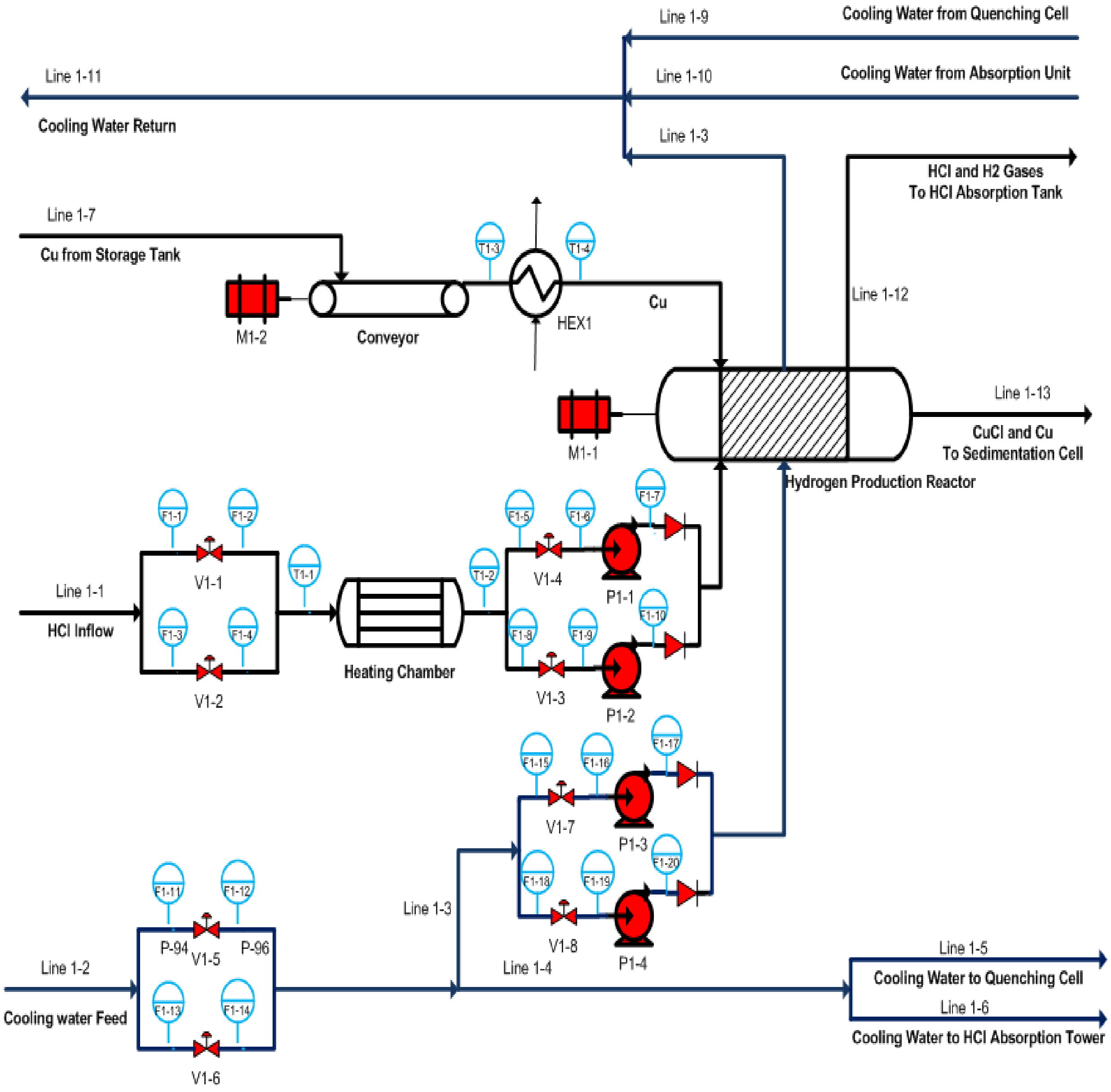

Fig. 4 Partial P&ID of the hydrogen reactor unit (part 1)

In Fig. 5, molten Cu-Cl and copper particles are fed into the sedimentation cell through Line 1-15. Subsequent to their separation at the cell, the copper particles are recycled and deposited into a copper storage tank through Line 1-16. A relief valve, RV1-1, was provided for surplus gas disposal as recommended in [9]. The molten Cu-Cl is fed into a quenching cell through Line 1-17. Flow measurements, F1-27 to F1-29, and F1-30 to F1-32, are used to provide the necessary data to control V1-11 & P1-7 and V1-12 & P1-8, respectively. Level, temperature and pressure sensors are provided for both the sedimentation cell and the quenching cell. The flow of water vapour outlet and water inlet of the quenching cell is controlled by V1-13 in Line 1-18 and V1-14 in Line 1-19, respectively. Flow measurements are provided for both streams.

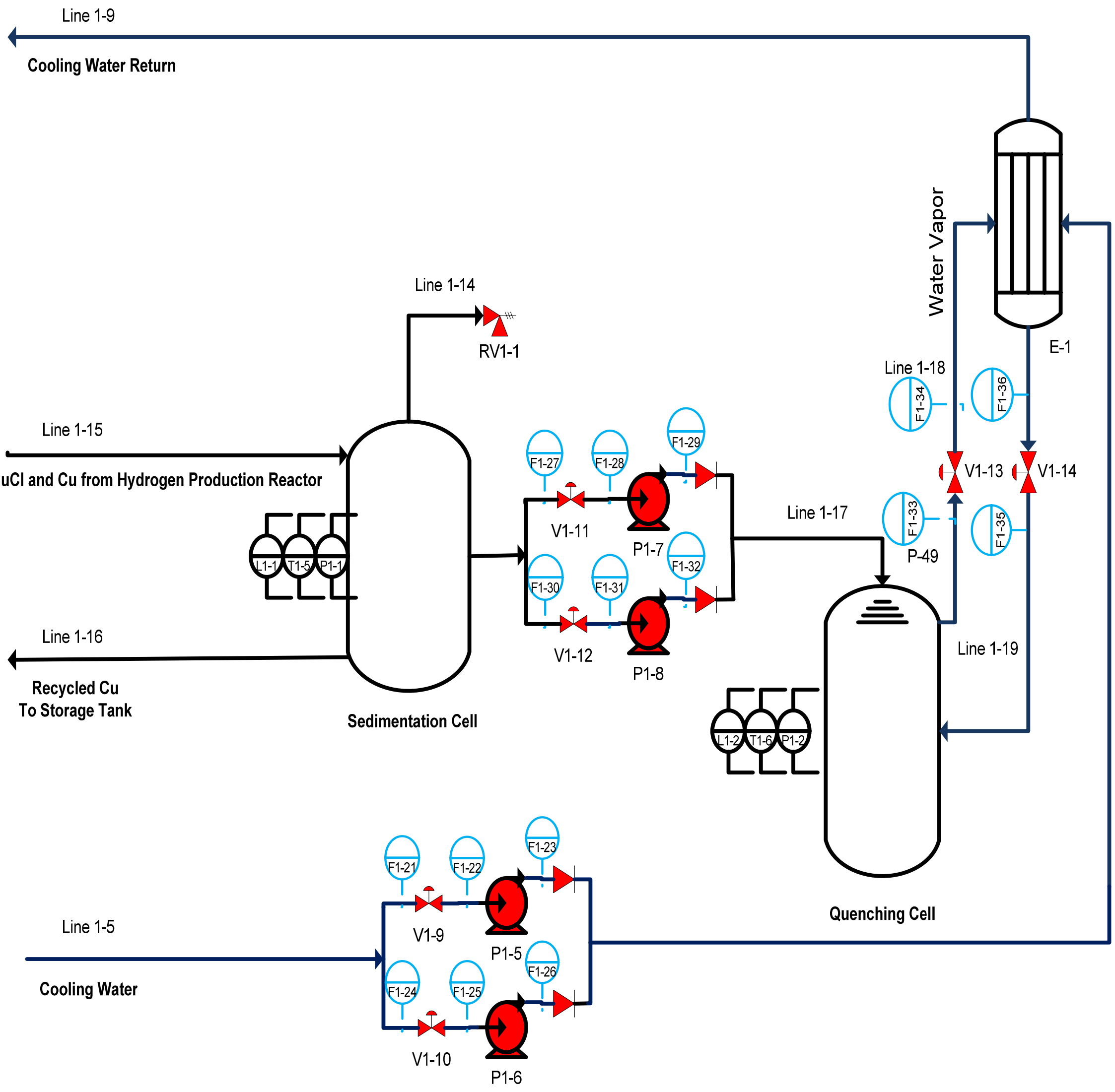

Fig. 5 Partial P&ID of the hydrogen reactor unit (part 2)

The HCl and H_2 gases exiting the hydrogen production reactor at a temperature of 450 ˚C in Fig. 4 should be cooled down to 60 ˚C prior to entering the HCl absorption tank in Fig. 6 [9]. Therefore, temperature measurements, T1-7 and T1-8 are used in controlling the cooling of the mixture in the cooling chamber in Fig. 6. The flow of the mixture is controlled by V1-19 and V1-20, where flow measurements are provided for both valves. An alkali storage tank supplies the

HCl absorption tank with an alkali solution through Line 1-20. Its flow is controlled by V1-15 and P1-11 or by V1-16 and P1-12 whose controllers receive flow measurements from F1-47 to F1-49 and F1-50 to F1-52, respectively. In Line 1-21, hydrogen is separated and then stored in a hydrogen storage tank. Flow, level and pressure sensors are used to provide the necessary measurements for the controllers of V1-21 and CP1-1 or V1-22 and CP1-2.

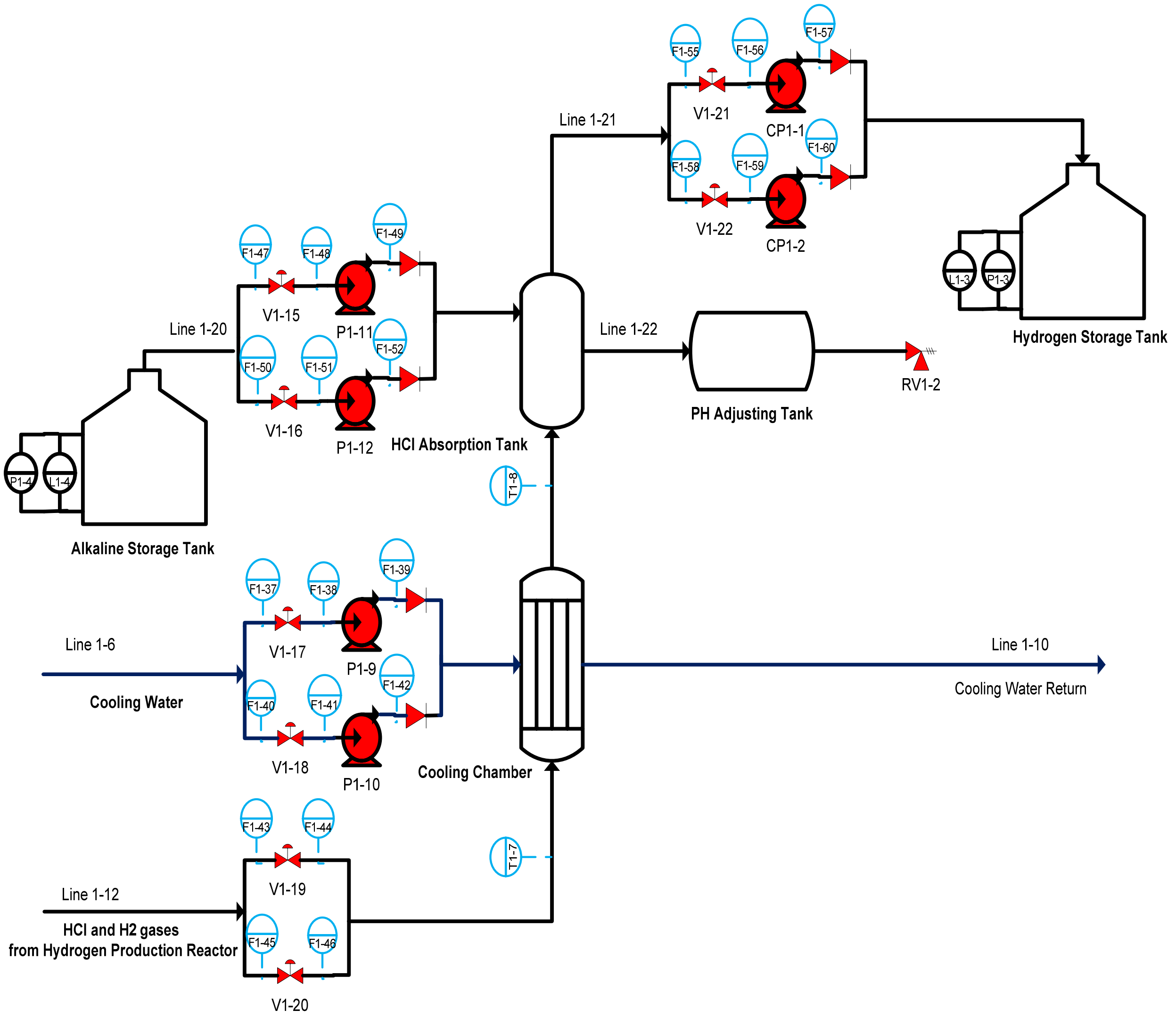

Fig. 6 Partial P&ID of the hydrogen reactor unit (part 3)

The redundancy of sensors, valves, pumps and compressors is essential for such safety-critical systems. Therefore, actuator and sensor redundancy was introduced at various places in the P&ID. For example, in Fig. 6, V1-21 and CP1-1 are the primary means of controlling the hydrogen flow to the storage tank and V1-22 and CP1-2 remain on standby.

4.2 Architecture of hydrogen reactor unit partition

For the hydrogen reactor unit shown in Fig. 3, the partition is composed of one group controller and several device controllers distributed throughout the process. The group controller is responsible for the following tasks:

- Communication with the PDS to receive commands and send information with regard to the amount of hydrogen produced and the hydrogen level in the hydrogen storage tank;
- Communication with the group controller of partition 2 (electrochemical cell) to control and monitor Cu inflow and CuCl production;
- Communication with the group controller of partition 4 (fluidized bed) to control and monitor the production of HCl gas;
- Communication with its device controllers to satisfy the production requirements while maintaining reliable and safe operation.

The device controllers of the hydrogen reactor partition are distributed throughout the process to control the auxiliary equipments of the hydrogen reactor unit. The tasks of the main device controllers for each of the three P&ID parts in Figures 4, 5 and 6 are as follows:

- Once the amount of the required hydrogen is specified, the device controller in the hydrogen production reactor (motor M1-1 in Fig. 4) will adjust the hydrogen production rate based on the input from the level measurements of the hydrogen storage tank (L1-3) and the flow rate of hydrogen in Fig. 6.
- In order to adjust the hydrogen production rate, communication must take place between the device controller of the hydrogen production reactor and the device controllers of Line 1-1, Line 1-7, and Line 1-3 in Fig. 4, to control the inflow of HCl gas, Cu particles and cooling water, respectively.
- In Fig. 5, the device controller of the quenching cell communicates with the group controller to provide feedback on the amount of CuCl production. It also communicates with the controllers of V1-13 and V1-14 to adjust the rate of its liquid water inflow and vapour outflow.
- The device controller of the sedimentation cell of Fig. 5 communicates with the group controller to provide feedback on the amount of Cu production. The controller also communicates with the controllers of the pumps and valves along Line 1-17 to control the inflow of molten CuCl to the quenching cell. It also communicates with the controller of the relief valve, RV1-1, to control its opening position.
- In Fig. 6, the device controller of the cooling chamber communicates with the controllers of valves, V1-19 or V1-20, to determine the flow rate of HCl and H_2 gases into the chamber. It also communicates with the controllers of the equipments of Line 1-6 to control the inflow of cooling water to the chamber.

- The controller of the HCl absorption tank shown in Fig. 6 communicates with the controllers of the valves and pumps of Line 1-20 to adjust the flow rate of the alkali solution to the absorption tank. It also communicates with the controllers of the valves and pumps of Line 1-21 to adjust the flow rate of the hydrogen gas to be stored in the storage tank.

5. Conclusion

In this paper, a DCS design is proposed for the nuclear-based Cu-Cl thermochemical hydrogen production cycle. The architecture of the DCS for the overall plant is presented. Five partitions are responsible for the control and monitoring of the five reactor units. The communication network and network protocols for the DCS are given. There are three network levels: information network, control network and field network. The hydrogen reactor unit is used as a case study where the functions of its group controller and device controllers are explained with reference to the P&ID created for the process.

6. References

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