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Development of an Intelligent System for Monitoring and Diagnosis of the Carbon Dioxide Capture Process

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ABSTRACT. The technology of amine-based carbon dioxide (CO_2) capture has been widely adopted for reducing CO_2 emissions and mitigating global warming. The primary research objective in the field of post-combustion CO_2 capture process system is to improve effectiveness and efficiency of the process. Extensive literature review of the research showed that the dominant approach was to investigate the behaviors of the aqueous amine solvents for enchancing CO_2 capture efficiency. As the operation of an amine-based CO_2 capture system is complicated and involves monitoring over one hundred process parameters and careful manipulation of numerous valves and pumps, automated monitoring and process control can be a fruitful approach to enhance efficiency of the CO_2 capture process system. In this study, artificial intelligence techniques were applied for development of a knowledge-based expert system that effectively monitors and controls the CO_2 capture process system so as to enhance CO_2 capture efficiency. The Knowledge-Based System for Carbon Dioxide Capture (KBSCDC) was implemented with DeltaV Simulate (trademark of Emerson Corp., USA). DeltaV Simulate provides control utilities and algorithms which support the configuration of control strategies in modular components. The KBSCDC can conduct real-time monitoring and diagnosis, as well as suggest remedies for any abnormality detected. Also, the control strategies applied to the control devices of the process are simulated in KBSCDC. The expert system enhances performance and efficiency of the CO_2 capture process system because it supports automated diagnosis of the system should any abnormal conditions occur. In this way, costly downtime and maintenance are avoided.

Keywords: knowledge-based system, monitoring, control, diagnosis, carbon dioxide capture process system

1. Introduction

Combustion of fossil fuels in power generation and in various industrial processes such as cement manufacture and hydrogen production emits large amounts of CO_2 (Rao and Rubin, 2002; Yoshida and Matsuhashi, 2009). It is reported that CO_2 is a primary greenhouse gas and causes enhanced global warming. Due to increasing public concern about environmental pollution and climate change, the post combustion CO_2 capture technology is widely regarded as a useful technology for reducing industrial CO_2 emissions.

The research on post-combustion CO_2 capture has been ongoing in the last two decades, and its primary objective is to improve efficiency of the CO_2 capture process system using various approaches. The first approach is to study the behaviors of different aqueous amine solvents used for CO_2 absorption. The behaviors of amine solvents are evaluated based on their reaction kinetics with CO_2, CO_2 absorption capacity, degradation resistance, corrosiveness, and heat consumption for regeneration (Alper, 1990; Aroonwilas and Paitoon, 1997; Ramachandran et al., 2006; Reza and Trejo, 2006; Sakwattanapong et al., 2006; Supap et al., 2006; Gabrielsen et al., 2007; Henni et al., 2008; Kim et al., 2008; Zhang et al., 2008; Zeng et al., 2011). The second approach is to select appropriate solvent based on the requirements and features of different applications to bring down the energy penalty (Tontiwachwuthikul, 1996; Chakma, 1997; Chakma, 1999; Lawal et al., 2005; Idem et al., 2006; Ma'mun et al., 2007; Kim et al., 2011). It has been suggested that the key consideration for selecting the appropriate solvent for the CO_2 capture process included feed gas characteristics, the treated gas specifications, and solvent characteristics. The third approach is to unravel and study the key parameters in the CO_2 capture process system which are related to plant performance and efficiency. Some process parameters have been discovered to be significant in determining the CO_2 capture performance and effecttiveness; they include reboiler heat duty, steam pressure, CO_2 loading of the solvent, and solvent circulation rate, etc (Leci, 1997; Roongrat et al., 2005; Huang et al., 2011; Vitse et al., 2011).

Operation of an amine-based CO_2 capture system is a complicated task which includes monitoring a large number of process variables including pressure, flow, and temperature, and manipulating numerous valves and pumps. Although the

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computerized control systems that monitor the process can generate real-time process variable values, it is still difficult for the operators to effectively monitor the process data, analyze current states of the system, and detect and diagnose process abnormalities. Therefore, automated monitoring and process control can potentially be a fruitful approach for enhancing efficiency of the CO_2 capture process system. As research effort that focuses on this approach has been scant, we aim to fill this gap in research by developing a knowledge-based expert system that can automatically monitor, control, and diagnose the CO_2 capture processes system at the International Test Centre for CO_2 Capture (ITC) located at the University of Regina in Regina, Saskatchewan of Canada. Some sample studies related to amine-based CO_2 capture process conducted at ITC include (Aroonwilas and Veawab, 2004; DeMontigny et al., 2006; Henni et al., 2006; Supap et al., 2011).

The system to be presented in this paper is called the Knowledge-Based System for Carbon Dioxide Capture (KBS-CDC). The KBSCDC can help the operator monitor the process conditions by continuously comparing the measured values of the parameters with desired operating ranges. Deviations from the normal ranges would set off an alarm to advise the operator that an abnormality has occurred. The system also can diagnose the abnormal conditions and suggests the appropriate remedial control actions. Hence, the expert system assists the operator in early and accurate detection and diagnosis of abnormal conditions, thereby reducing downtime and increasing efficiency of plant operations. This knowledge-based expert system was implemented with DeltaV Simulate (trademark of Emerson Corp., USA).

The paper is organized as follows: Section 2 presents the background literature relevant to the amine-based CO_2 capture technology and inferential modeling technique (IMT). Section 3 describes the development process of the knowledge base. Section 4 presents design and configuration of the system on DeltaV Simulate. Application of the system is demonstrated using a case study in Section 5. Section 6 gives a conclusion and includes some discussion about future work.

2. Background Literature Review

2.1. Amine-based CO_2 Capture Process at ITC

The CO_2 capture system includes 16 reaction instruments as shown in Figure 1 and a brief explanation about the CO_2 capture process is given as follows. Prior to CO_2 removal, the flue gas is cooled down and the impurities such as sulfur oxide (SO_x) and nitrogen oxide (NO_x) are removed as much as possible in the inlet gas scrubber (1). The pre-treated flue gas is passed into the absorber (2) and contacted the lean amine solution pumped from the lean amine storage tank (3). With the high temperature steam provided by the boiler (4), the amine solution selectively absorbs CO_2 from the flue gas. The CO_2-free flue gas is passed into the off-gas scrubber (5) to cool down and then vented into the atmosphere. The CO_2-rich amine carrying CO_2 is passed through the rich amine surge

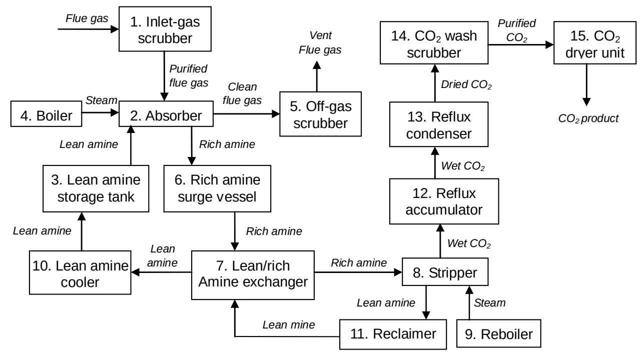

Figure 1. Process diagram of CO_2 capture plant at ITC.

vessel (6), and then sent to the lean/rich amine heat exchanger (7), where the rich amine is heated to about 105 °C, and then enters the stripper (8). The reboiler (9) under the stripper provides the steam to extract CO_2 from the rich amine solution and regenerate lean amine solution. Most of the lean amine passes through the lean amine cooler (10), where the lean amine is cooled down and recycled for further CO_2 absorption. A small portion of the lean amine is fed to a reclaimer (11) to remove degradation by-products. The residual amine passes through the reflux accumulator (12) and flows back to the stripper. The wet CO_2 product is passed through a reflux condenser (13) to condense the water and then enters a CO_2 wash scrubber (14), where the CO_2 gas is cooled down and then sent to a dryer and purification unit (15) to produce food grade CO_2.

2.2. Inferential Modeling Technique

To develop a knowledge-based system, it is critical to acquire expertise that can be encoded in the knowledge base. For acquiring knowledge on the CO_2 capture process system, we adopted the Inferential Modeling Technique (IMT) derived from the Inferential Model. An inferential model is a generic categorization of knowledge types, which functions as a "conceptual map" to aid the knowledge engineer in identifying and classifying elements of the elicited expertise (Chan, 2000; Nguyen and Chan, 2006). Based on this "map", the IMT supports "an iterative-refinement of knowledge elements in a problem-domain that provides top-down guidance on the knowledge types required for problem solving" (Chan et al., 2002). The resulting inferential model consists of the following four levels of knowledge:

(1) Domain knowledge consists of objects, attributes, values, and relations. The objects include a set of concrete domain objects. The attributes describe the properties of the objects, which can be defined as a set of functions that receive input values and return output values. The relations describe the relationships among the objects or the attributes.

(2) Inference knowledge consists of abstract objects. These inference level objects can be described with inference relations and strength of inferences. The inference relations identify different types of relations among sets of abstract objects; a strength factor is associated with each inference

relation and represents the relative inferential significance of the relation.

(3) Task knowledge consists of a set of procedures or behaviours which are performed to complete a goal. A task is accomplished by means of a method that invokes the domain and inference objects or relations involved in this task. One task can be decomposed into a number of subtasks, and the objective of this task is accomplished by coordinating all the sub-goals.

(4) Strategy knowledge is defined as the knowledge used during the diagnostic process to decide what is the most opportune choice to make or, alternatively, to judge if it is worth executing a certain action with respect to other possible actions.

The IMT was applied and the domain and task knowledge specified were used in the process of knowledge base development for the KBSCDC.

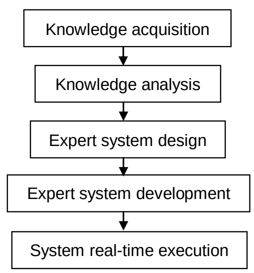

Figure 2. Flowchart of the expert system development.

3. Development of a Knowledge Base

As shown in Figure 2, the development of the expert system involved the following five steps: knowledge acquisition, knowledge analysis, expert system design, system configuration, and real-time execution.

The knowledge base in this study was developed in three phases: knowledge acquisition, knowledge analysis, and knowledge representation. In the process of knowledge acquisition, the first author acted as the knowledge engineer and interacted with the chief engineer of ITC to acquire problem-solving knowledge about the domain. During the phases of knowledge analysis and representation, the knowledge engineer analyzed the verbal information collected from the expert and configured them into a conceptual model. The IMT was applied in knowledge analysis, and the knowledge was formalized into an inferential model. The IMT decomposed knowledge into the two levels of domain knowledge and task knowledge.

3.1. Domain Knowledge

The objects in the plant can be classified into two categories: static and dynamic. The static objects include the constructive components of the plant, which can be divided into the two classes of reaction instruments and control devices. The control device involves two subclasses of pumps and valves. The dynamic objects include the substances that circulate and react in the plant, i.e., the water, amine solvent, and gases. The classification of objects is shown in Figure 3, and the details are described in the following sections.

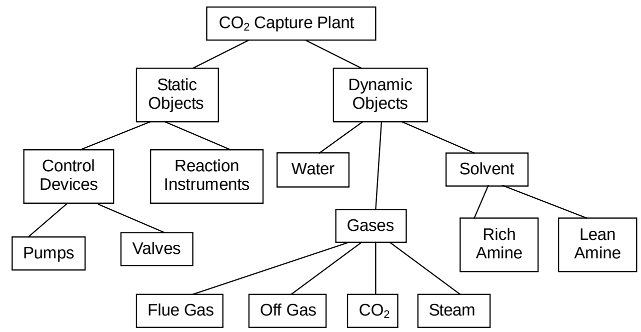

Figure 3. Classes and objects in CO_2 capture plant.

3.1.1. Reaction Instruments

There are 16 primary reaction instruments involved in the plant. They are grouped into three main classes based on their functions and listed as follows:

(1) Pre-treatment section, which includes the steam boiler, micro turbine, inlet-gas scrubber;

(2) Absorption-based CO_2 section, which includes the absorber, off-gas scrubber, lean amine storage tank, lean amine cooler, rich amine vessel, lean/rich amine exchanger, stripper, reboiler, and reclaimer;

(3) Post-conditioning section for product purification, which includes the reflux condenser, reflux accumulator, CO_2 wash scrubber, and CO_2 dryer unit.

The attributes of the reaction instruments include the temperature, pressure, or level of the instruments and the attributes of their output dynamic objects.

3.1.2. Control Devices

The control devices are used for manipulating the fluids circulating in the process, and they include two subclasses of valves and pumps. The valves are classified based on their control mechanisms: PID (proportional-integral-derivative) control valves and solenoid valves. All the solenoid valves are used for controlling water, and the PID valves are subdivided into the following four groups based on the substances they manipulate: (1) steam supply control valve, (2) amine control valve, (3) water control valve, and (4) gas control valve.

All the PID control valves in the plant are identified by five attributes: the three system attributes of (1) tag number (the label for a valve/pump), (2) name (the brief description), (3) type (the mechanism of a valve/pump), and two design attributes of (4) location (where the valve/pump is installed in the plant), and (5) distribution flow (the dynamic object which a valve/pump controls). The solenoid valves can be identified by the additional attribute of status, which describes their ON/OFF state under normal conditions.

Like the solenoid valves, all the pumps can be identified

Table 1. Samples of Valve/Pump

Tag	Name	Type	Distribute Flow	Location	Status
FCV-600 (Valve)	Lean amine to absorber control valve	PID control valve	Amine solvent	Between absorber and lean amine storage tank	N/A
B-200 (Pump)	Inlet flue gas blower	Gas blower	Flue gas	Between flue gas scrubber and absorber	ON

by six attributes of tag number, name, type, location, distribution flow, and status. A sample valve and a sample pump are given in Table 1.

3.1.3. Dynamic Objects and Their Attributes

The dynamic objects include amine solvent, water, and gas. The amine solvents are classified into lean amine and rich amine based on the amount of CO_2 in the solution. The gases include flue gas (with CO_2), off gas (free of CO_2), CO_2, and steam.

All the dynamic objects are described by the three attributes of temperature, pressure, and flow rate. Since the dynamic objects react with other substances as they circulate through the entire process, the values of their attributes are constantly changing. Therefore, the properties of dynamic objects at any particular location are identified by the tag of the sensor, and the knowledge engineer defined the attributes of the dynamic components as the attributes of the reaction instrument from which they flow.

There are two reasons for organizing the attributes of dynamic objects in this way. Firstly, the performance of the reaction instrument directly impacts the attributes of its output dynamic objects. Secondly, this approach enables straightforward examination of the attributes of dynamic objects at different phases in the process, thereby facilitating design and construction of the KBSCDC. The method of knowledge organization allows over one hundred process parameters in the plant to be grouped into 16 reaction instrument groupings. Therefore, the entire system can be viewed in terms of sixteen reaction components, their related attributes or process parameters, and their related valves/pumps.

3.2. Task Knowledge

The main task of the system is to monitor all the reaction instruments so as to ensure they operate under desirable conditions. The task of monitoring each reaction instrument involves the subtasks of monitoring its related process parameters to maintain their values within the desirable operating ranges. For example, monitoring of the inlet-gas scrubber consists of the four subtasks of: (1) controlling the flow rate of flue gas into the absorber (FT-200), (2) controlling the temperature of flue gas into absorber (TE-201), (3) controlling the wash water flow rate of scrubber (FT-420), and (4) controlling the inlet-gas scrubber water level (LC-410). The knowledge engineer identified the normal operating ranges of these parameters. The operating range of the sample parameter of wash water flow rate (FT-420) is given in Table 2.

The system monitors the operating conditions of the CO_2 capture plant by constantly comparing the measured values of the parameters with the normal value ranges. If the value of a parameter falls outside of the normal ranges, it indicates that some abnormal operating conditions have occurred. In response, the system activates the alarm, diagnoses the abnormal state, and then suggests the remedial control actions that would address the abnormal situation.

Table 2. Sample Parameters and Their Normal Operating Ranges

Tag	Parameter	Unit	Limit	Value
FT-420	Off gas scrubber wash water flow rate	kg/min	High	37.0
			Low	5.0
PT-670	Reclaimer pressure	Kpa	High	22.8
			Low	12.0

The diagnosis and remedial control actions are determined by various conditions. For example, the details of diagnosis and control actions for the sample parameter of wash water flow rate (FT-420) are given in Table 3. If the wash water flow rate (FT-420) of the inlet-gas scrubber is less than 5.0 kg/m, a warning is given to the operator. The diagnosis of the situation is that the overly low flow rate of wash water could be caused by the closed water circulation pump P-420. Therefore, the remedial control action is to open pump P-420 so as to restart water circulation between the water tank and the inlet-gas scrubber. However, if P-420 is already open, then the PID valve FCV-420 should be opened to increase water flow.

4. System Design and Implementation

4.1. System Design

The intelligent system of KBSCDC was implemented on DeltaV Simulate (a trademark of Emerson Corp., USA). DeltaV Simulate provides control utilities which enables the configuration of control strategies in small modular components, which link algorithms and conditions, and provide control over the field devices such as pumps and valves. The modules can communicate directly with each other, or they can be coordinated by other modules to implement higher-level control strategies. The implementation of KBSCDC on DeltaV involves a hierarchy of the five levels of plant area, module, algorithm, function block, and parameter. The plant areas are logical divisions of the process control system, which can be based on physical plant locations or main process functions. A plant area consists of a number of modules, and each module is a logic control entity responsible for configuring the control strategies. It contains algorithms, alarms, and other characteristics that define the process control. The algorithms define the logic steps that describe how the

Table 3. Diagnosis and Control Strategies for Wash Water Flow Rate (FT-420)

Object	Task	Conditions	Diagnosis and Controlling Actions
Inlet-Gas Scrubber	Control wash water flow rate (FT-420)	FT420 < 5.0kg/min	Warning is given Diagnosis: The wash water flow to water tank is low or stopped by the closed water circulation pump-420; Remedial Control Action: Open P-420 to restart water circulation between water tank and scrubber; otherwise, open up FCV-420 to increase volume of water returning to water tank if P-420 is open;
		FT420 > 37.0kg/min	Warning is given Diagnosis: The volume of wash water between the off gas scrubber and water storage tank is too high; Remedial Control Action: Close FCV-420 to reduce wash water flow from the scrubber wash water storage tank;

module behaves and how the tasks are accomplished. In this intelligent system, the function block diagrams (FBD) were used to continuously execute control strategies. A FBD is made up of interconnected function blocks, which process the incoming signals and in turn send signals to the control devices. Each function block contains a standard process control algorithm and parameters that customize the algorithm to perform a particular function in the process control.

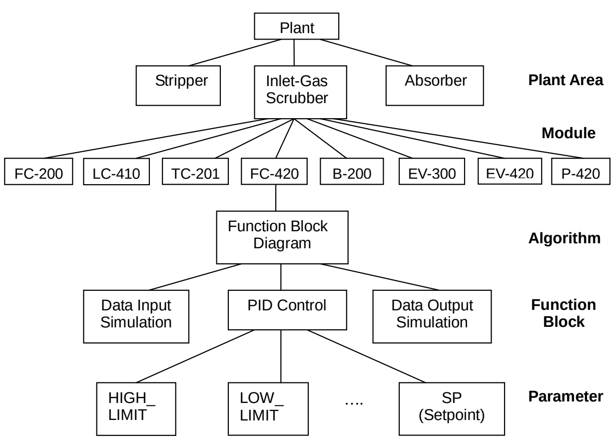

Figure 4. Implemented hierarchy of the KBSCDC in DeltaV Simulate.

The five-level hierarchy of the KBSCDC system supports a top-down approach for encoding knowledge into DeltaV Simulate. Sample components of each level are given in Figure 4, which illustrates components of the system constructed on DeltaV Simulate and the system details are described below.

Three sample plant areas include the areas for the stripper, the inlet-gas scrubber, and the absorber. In this discussion, the inlet-gas scrubber is used as an example to illustrate how a plant area is constructed. The plant area of inlet-gas scrubber contains eight modules. Four of these are PID valve control modules for the process parameters of: (1) flue gas flow rate into absorber (FC-200), (2) inlet-gas scrubber water level control (LC-410), (3) temperature of flue gas to absorber (TC-201), and (4) wash water flow rate of inlet-gas scrubber (FC-420). The other four modules are 2-state control modules for the pumps and solenoid valves of: (1) flue gas blower (B-200), (2) make up water control valve (EV-300), (3) wash water control valve (EV-420), and (4) wash water pump (P-420). The algorithm used in the module of wash water flow rate into absorber (FC-420) is represented in a function block diagram, which consists of the function blocks of data input simulation, data output simulation, and primarily a PID control function. Since the KBSCDC system is not connected to the CO_2 capture plant at the current stage, the data input and output to the system are simulated by using function blocks. The PID control function block contains the most important parameters, which includes the set-point (SP) of the PID control and alarm activation limits, whose variable names in the system are HIGH_LIMIT and LOW_LIMIT.

4.2. System Implementation

The DeltaV Simulate consists of the three modules of DeltaV Explorer, Control Studio, and DeltaV Operate, and each of the modules performs a specific function in the construction of the intelligent system. The DeltaV Explorer is a navigation tool which enables the user to construct and view the overall system including the hierarchy of plant areas and modules. The Control Studio enables the user to design and graphically create the individual modules and templates that make up the control strategy. The DeltaV Operate has two modes of configure and run. The configure mode supports building the process graphics and developing the user interface. The run mode allows the operator to monitor and control the process by interacting with the system through the user interface.

4.2.1. Plant Areas

The division of plant areas and specification of modules were completed in DeltaV Explorer, as shown in Figure 5. The overall structure of the system, which consists of 16 reaction instruments or plant areas can be viewed in the left

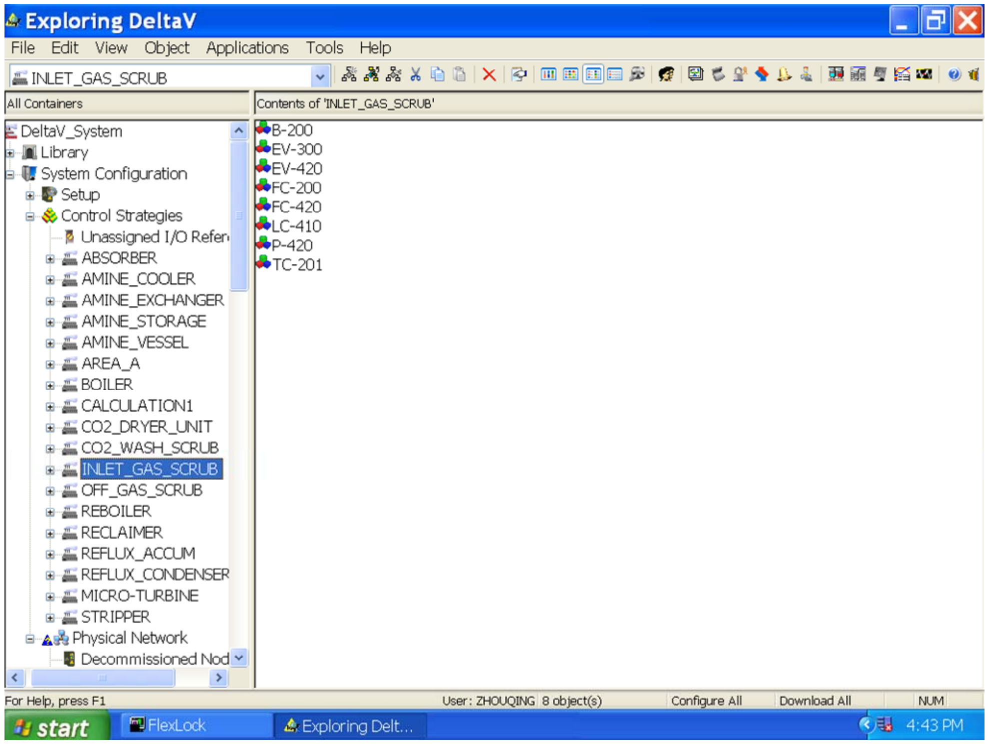

Figure 5. Overall structure and modules in plant area “inlet-gas-scrubber”.

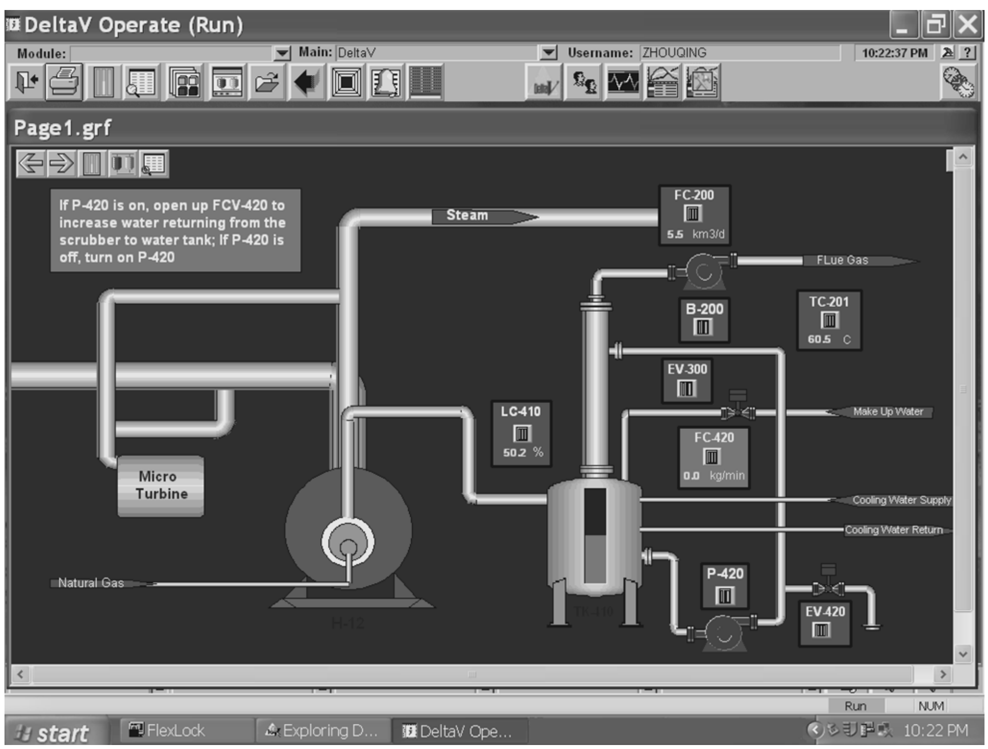

Figure 6. System interface for case study.

panel. One sample plant area of “inlet-gas-scrubber” is selected and the eight modules in this plant area are shown in the right panel. These modules correspond to the modules shown at the module level in Figure 4.

4.2.2. Control Modules

A control module is constructed in the module of Control Studio by connecting various function blocks with graphic wires, through which data values can pass. The function blocks are executed in a logical order, and the execution determines the behaviour of the module. The details of the PID function block are explained in the next section.

4.2.3. Function Blocks and Parameters

The alarm detection function is implemented in the PID block, which contains a set of process parameters and their associated normal operating ranges. There are three classes of parameters for alarm detection: ALARM_TYPE, ALARM _LIMIT, and ALARM_ACT.

ALARM_TYPE specifies two types of alarms for warning conditions: HIGH_ALARM and LOW_ALARM. ALARM _LIMIT specifies the alarm limits or the values at which the alarms are activated. Based on the two types of alarms, there are two alarm limits: HIGH_LIMIT and LOW_LIMIT. The system compares these limit values to the present value to determine if an alarm condition exists, which is indicated by true/false (1/0) state of the ALARM_ACT. Corresponding to ALARM_LIMIT that includes HIGH_LIMIT and LOW_ LIMIT, ALARM_ACT includes HIGH_ACT and LOW_ACT. When any alarm condition exists or when the present value is lower than or exceeds the values of ALARM_LIMIT, ALARM_ACT is set to true and the alarm is activated. For example, the desirable operating range of FT-420 is between 5.0 kg/min and 37.0 kg/min. Therefore, the high limit (HIGH_ LIMIT) of FT-420 is 37 and the low limit (LOW_ LIMIT) is 5. If the present value (PV) of FT-420 is higher than 37.0 kg/min (HIGH_LIMIT), HIGH_ACT becomes true and the alarm for HIGH condition is activated. If the present value (PV) of FT-420 is lower than 5.0 kg/min (LOW_LIMIT), LOW_ACT becomes true and the alarm for LOW condition is activated. If the present value is neither higher than 37.0 kg/min nor lower than 5.0 kg/min, neither HIGH_ACT nor LOW_ACT becomes true and no alarm is activated. The alarm is displayed on the user interface to remind the operator of the abnormal condition. The desirable operating ranges of the process parameters are not only used for alarm activation, but also trigger the diagnosis displays, which is the message box on the top left corner of the screen shown in Figure 6.

5. Case Study

A scenario in which the inlet-gas scrubber wash water flow rate (FT-420) is in the abnormal condition is shown in Figure 6. The current value of FT-420 shown on the panel of FC-420 is 0 kg/min, which is lower than its normal low limit of 5.0 kg/min and indicates the water circulation between the inlet gas scrubber and water tank has stopped because the pump is shut. The alarm is activated and displayed on the interface, so that the panel for FC-420 is turned to the light gray color. The diagnosis and control suggestion being sent to a message board on the user interface says: "If P-420 is on, open up FCV-420 to increase water returning from the scrubber to water tank; if P-420 is off, turn on P-420." The red color of pump P-420 indicates its closed status. Therefore, according to the control suggestion, P-420 should be opened so the water circulation will restart.

Figure 7. Faceplate for control pump P-420.

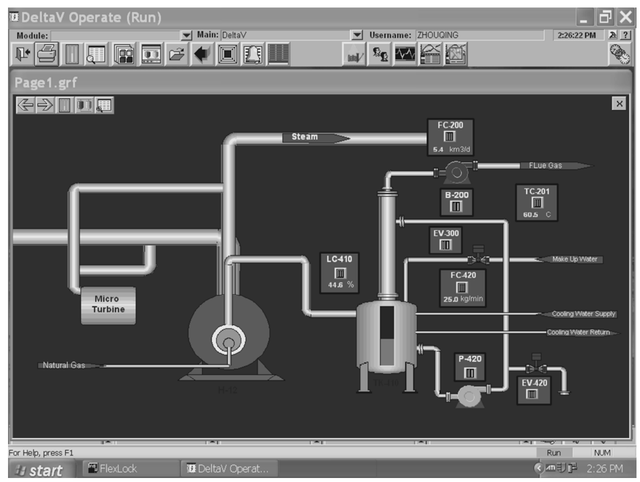

Figure 8. Case study back to normal operation.

The control action for P-420 is activated using the face- plate shown in Figure 7. Pushing on the state button of "START" would start the motor of P-420 so that it reaches its target running mode. By opening P-420, water circulation will restart so as to restore the normal operation of FT-420. Figure 8 shows the interface which indicates FT-420 has returned to normal operation. The light gray color of pump P-420 indicates that P-420 is running; the current value of FT-420 shown on the panel of FC-420 indicates that the water circulation rate has increased to 25.0 kg/min, which is within the normal operating range of 5.0 kg/min to 37.0 kg/min. Since the remedial action has been applied to address the problem which triggered the alarm, the alarm and the diagnosis message both disappeared from the top left corner of the interface.

6. Conclusions

The knowledge-based expert system for monitoring and control of the CO_2 capture process system is presented in this paper. The system helps to enhance system performance and CO2 capture efficiency by dramatically reducing the time for problem diagnosis and resolution when an abnormal operating condition has occurred. Operators can use the expert system as a decision-support tool in operating and controlling the plant; it also can be used for training novice operators. The knowledge base of the system can be extended with future refinement or updates. There is a weakness in the current vision of the expert system. Since there are sixteen components involved in the CO_2 capture process system, an abnormal condition can be caused by incorrect performance of more than one component or parameter. However, the system in its current version can only deal with abnormal operation of one component at a time. To address this limitation, future research work will focus on enabling diagnosis and control of multiple faulty components or parameters so as to improve the capability and reliability of the system.

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