UNIVERSITY OF WATERLOO

Department of Chemical Engineering

ChE 524 Process Control Laboratory

Instruction Manual

January, 2001

Revised:
May, 2009

Experiment # 2 - Double Pipe Heat Exchanger

Experimental Equipment:

The double pipe heat exchanger consists of six lengths of concentric tubing set out as shown in Figure 1. Hot oil flows through the center tube in all six sections. In the first three sections, saturated steam is supplied to the outer tubes in order to heat the oil. In the latter three sections, process water flows counter-currently in order to cool the oil. The cooled oil then flows to a storage/surge tank from which it is recirculated to the first section of the heat exchanger. The physical properties and potential hazards of the oil are presented in the attached MSDS. In order to measure the temperatures of the oil and water, eleven type-T thermocouples are located in thermowells in the heat exchanger. Four of these thermocouples of interest for the experiment are connected to an interface to a computer, whereas the other thermocouples are connected to a digital display. The oil and water flow rates are measured by flow meters that are also connected to a computer interface. The oil flow is controlled using a ball valve (Model V9001 CNT) and the water flow rate is controlled by a gate valve (Model V1430 JNT). Both valves are connected to the interface. The pressure of saturated steam used is controlled using a hand operated globe valve and is measured on a local pressure gauge. All sections of the heat exchanger are insulated to prevent heat loss and reduce the risk of burns to the operator.
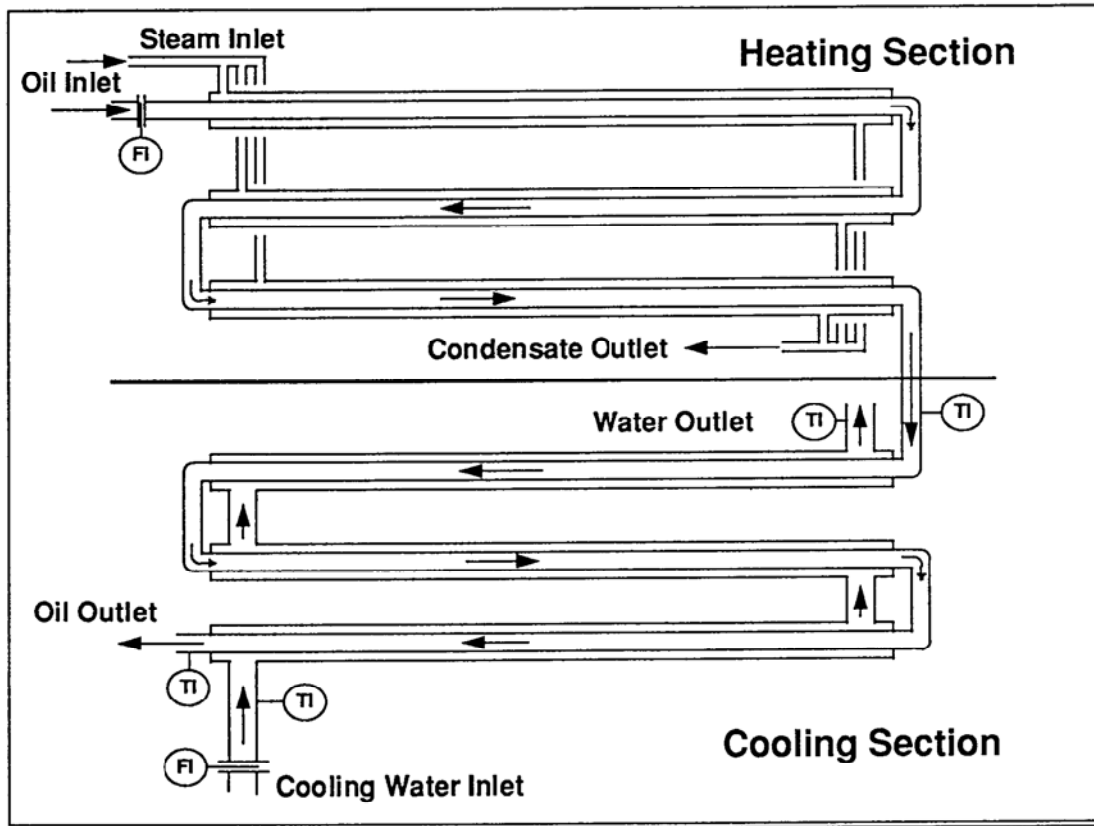
Figure 1: Double Pipe Heat Exchanger Apparatus

The system is controlled using a MPC control algorithm written in MATLAB and interfaced through National Instrument's LabVIEW software and DAQ hardware.

Safety Considerations:

1. Safety glasses must be worn at all times in the laboratory.
2. No food is to be consumed in the laboratory at any time.
3. The proper safety equipment (insulated gloves) must be worn when coming into contact with process equipment (excluding computer).
4. Care should be taken to prevent contact of process water and electrical equipment.

MPC Tutorial for the Double Pipe Heat Exchanger

Equipment:

Personal Computer
4 Type T thermocouples
(inlet/outlet oil inlet/outlet water #4, #7, #8, # 11)
2 Flow meters
(oil, water)
(The computer and the instruments should already have been connected)

Software:
- A MPC GUI controller program written in National Instrument's LabVIEW and Mathwork's MATLAB software in a single application
- NEXUS software for offline system identification (e.g., Excel, MATLAB, etc.)

Introduction to MPC Theory

Multivariable Systems

Multivariable systems with interaction are described by a transfer function matrix. Figure 1 depicts a typical two input/two output system block diagram.
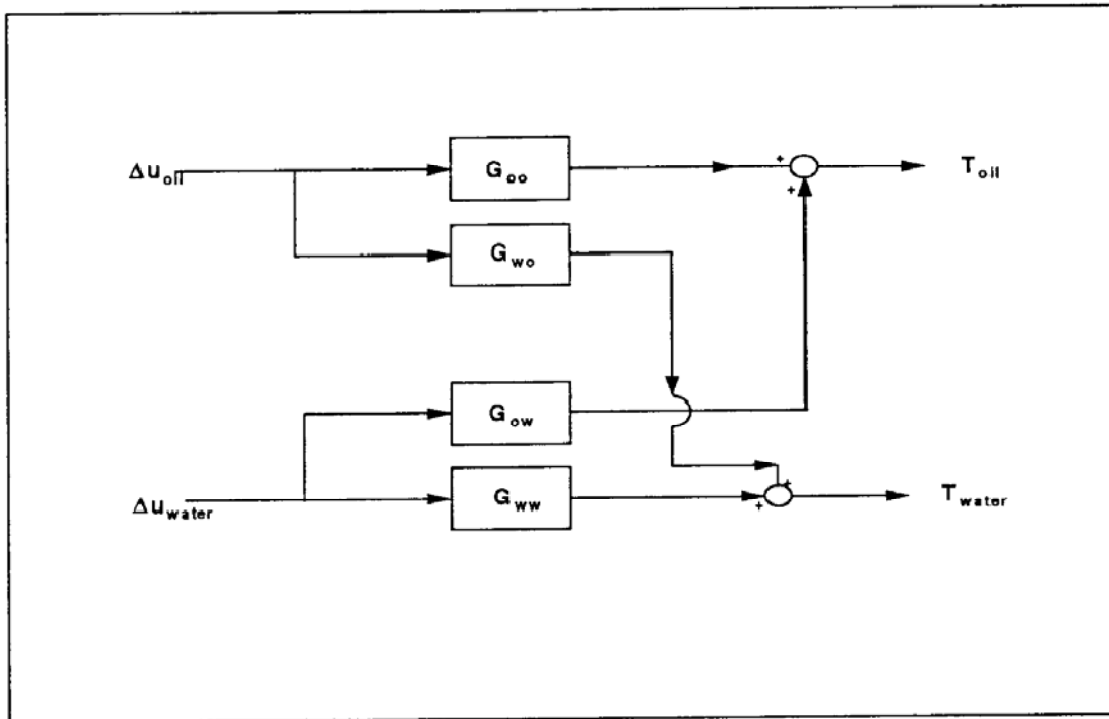

Figure 1: Block Diagram of Multivariable Process

The effect of changes in the manipulated variables on the outputs can be described by:

$$\begin{pmatrix} T_{oil} \\ T_{water} \end{pmatrix} = \begin{pmatrix} G_{oil\text{-}oil} & G_{oil\text{-}water} \\ G_{water\text{-}oil} & G_{water\text{-}water} \end{pmatrix} \begin{pmatrix} \Delta\mu_{oil} \\ \Delta\mu_{water} \end{pmatrix} \qquad (1)$$

where:
- $G_{oil\text{-}oil}$ relates the outlet oil temperature to changes in the oil flow rate
- $G_{oil\text{-}water}$ relates the outlet oil temperature to changes in the water flow rate
- $G_{water\text{-}oil}$ relates the outlet water temperature to changes in the oil flow rate
- $G_{water\text{-}water}$ relates the outlet water temperature to changes in the water flow rate

The off-diagonal elements of the matrix ($G_{\text{oil-water}}$ and $G_{\text{water-oil}}$) represent interactions in the system and make control more difficult. The optimal pairings of manipulated and controlled variables can be determined using a relative gain array (RGA). Relative gain is defined in equation 2.

$$\lambda_{11} = \frac{\text{open} - \text{loop gain}}{\text{closed} - \text{loop gain}} = \frac{\left(\dfrac{\Delta T_1}{\Delta \mu_1}\right)_{u_2}}{\left(\dfrac{\Delta T_1}{\Delta \mu_1}\right)_{T_2}} \tag{2}$$

where λ_{11} is the relative gain.

If the value of the relative gain lies between 0.5 and 1.0, μ_1 should be used to control T_1. If λ_{11} lies between 0 and 0.5 μ_2 should be used to control T_1. If λ_{11} is greater than 1 or less than 0, however, there is strong interaction in the system and control will be difficult.

Model Predictive Control

Unconstrained model predictive control (MPC) is an advanced control strategy based on the prediction of future valves of process outputs for changes in manipulated variables. The controller will predict the future errors in the outputs and will attempt to minimize these errors by choosing the optimal set point changes for manipulated variables. Constrained model predictive control will also find the optimal set point changes for manipulated variables, though the optimal settings will be subject to constraints on the manipulated variables.

Future predictions of the output variables are based on step changes in the inputs at time k and the assumption that no future changes will be made in the inputs. The predictions are calculated by:

$$\tilde{T}_{\text{oil}}(k) = \tilde{T}_{\text{oil, prev}}(k) + S_{\text{oil-oil}}\Delta\mu_{\text{oil}}(k-1) + S_{\text{oil-water}}\Delta\mu_{\text{water}}(k-1) \tag{3}$$

where:

$\tilde{T}_{\text{oil}}(k)$ = predicted oil temperature at time k

$\tilde{T}_{\text{oil, prev}}(k)$ = prediction of oil temperature at time k made at time $(k-1)$

$S_{\text{oil-oil}}$ = response of oil temperature to a unit step change in oil flow

$S_{\text{oil-water}}$ = response of oil temperature to a unit step change in water flow

$\Delta\mu_{\text{oil}}(k-1)$ = change in oil flow rate at time $(k-1)$

$\Delta\mu_{\text{water}}(k-1)$ = change in water flow rate at time $(k-1)$

The temperature at time k is predicted by updating the previous prediction for new changes in the manipulated variables that occurred at time (k − 1).

MPC requires predictions of output variables several steps into the future. The number of prediction steps into the future is a user specified parameter known as the Prediction Horizon (P). The choice of prediction horizon is based on the stability of control required and the time available for computation. By increasing the prediction horizon, the controller will be more conservative and stability will be improved, though the time required for computation is also increased. For a prediction horizon greater than unity, equation 3 can be expressed in matrix form:

$$\tilde{T}(k) = M \bullet \tilde{T}(k-1) + S^{\mu} \Delta\mu(k-1) \tag{4}$$

<div align="center">where:</div>

$$\tilde{T}(k) = \left[\tilde{T}_{oil}(k), \tilde{T}_{water}(k), \ldots, \tilde{T}_{oil}(k+P-1), \tilde{T}_{water}(k+P-1) \right]^{T}$$

the prediction vector for the outlet temperatures P steps into the future.

$$M = \begin{bmatrix} 0 & I & 0 & \ldots & 0 \\ 0 & 0 & I & \ldots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \ldots & I \end{bmatrix}_{P \times P},$$

and I is an $n_u \times n_y$ identity matrix

$$S^{\mu} = \left[S_1^{\mu}, S_2^{\mu}, \ldots, S_P^{\mu} \right]^{T}$$

an $n_u \times n_y$ matrix of step responses.

$$\Delta\mu(k-1) = \begin{bmatrix} \Delta\mu_{oil}(k-1) \\ \Delta\mu_{water}(k-1) \end{bmatrix}$$

These predictions are used to predict the error in the controlled (output) variables over the prediction horizon by equation (5). The vector **R** is composed of the temperature set points specified by the user and the vector **W** is composed of corrections for differences between the measured output values and the predictions for these values.

$$\varepsilon(k+1|k) = R(k+1) - M \bullet \tilde{T}(k) - W(k+1|k) \tag{5}$$

<div align="center">where:</div>

$$R(k+1) = \left[T_{sp,oil}, T_{sp,water}, \ldots, T_{sp,oil}, T_{sp,water} \right]_{2P \times 1}^{T}$$

$$W(k+1|k) = \begin{bmatrix} T_{oil}(k) - \tilde{T}_{oil}(k) \\ T_{water}(k) - \tilde{T}_{water}(k) \\ \vdots \end{bmatrix}$$

W represents difference between current measured and predicted temperatures. The optimal flow set point changes were then computed by equation 6.

$$\Delta\mu(k) = K_{MPC}\varepsilon(k+1|k) \tag{6}$$

where:

K_{MPC} is the optimal gain matrix determined by the weighting factors, the prediction horizon, the control time interval, and the process transfer functions.

K_{MPC} is found by the least squares solution of the minimization in equation 7.

$$\min_{\Delta\mu(k)} \frac{1}{2}\left\{ \left\| \Gamma\left[\tilde{T}(k+1|k) - R(k+1)\right] \right\|^2 + \left\| \Lambda\Delta\mu(k) \right\|^2 \right\} \tag{7}$$

where:

$\Gamma \equiv$ output weighting factor
$\Lambda \equiv$ input weighting factor

This minimization is performed in pre-programmed functions in the MATLAB MPC toolbox embedded in the controller code.

This minimization is strongly dependent on the values of the weighting factors. An increase in the weighting factor for the output (Γ) will cause the controller to respond more aggressively to small deviations from the set points. Conversely, an increase in the weighting factor for the input (Λ) will cause the controller to respond less aggressively because, in order to minimize the function, the maximum allowable input change will decrease. The weighting factors are adjusted in order to tune the controller to provide the optimal response.

Instructions for ChE 524: Working on the LabVIEW GUI program:

General Items:
1. Copy the DPHE.vi executable file within a folder/directory in which you have at least 5MB of available memory. For convenience considering using path location either on your UW account drive(s) or on a USB memory stick. If possible, perform this before starting the first lab session.
2. Check with the teaching assistant to ensure that the equipment has been turned on and is ready for operation.
3. Run the DPHE.vi executable file. Recorded data will automatically be named with a <date and time stamp>.csv format into the path <DPHE.vi folder>\Data\.
4. Note that the graphic displays may be saved by a print-screen command or by right-clicking on any of the x-y plots and exporting the information as a bitmap image for quick reference.
5. **WARNING:** Do not open the **most recent** csv file until the DPHE.vi GUI is stopped or closed; or else the values in memory for the current trial may not be able to be recorded.
6. **WARNING:** The GUI has been designed to discard trials that are either greater than 3 hours or more than 32,000 samples in length. Therefore it is suggested to toggle between "MONITOR DATA" and "RECORD DATA" where practicable to begin a new trial.

Session One Items – System Identification:
More details about this procedure arte given in Appendix A.
1. After the DPHE.vi is running, ensure that the CONTROL MODE slider selector switch is in the "SESSION 1 System Identification" position.
2. Start with the toggle selector switch in the down, "MONITOR DATA", position.
3. Initiate nominal steady-state conditions by selecting a manual position for both the oil and water valves. The position (percentage of opening) of the valve may be controlled by either the slider bar or by typing in a numerical value.
4. Monitor the process conditions and wait for steady-state conditions.
5. Once the system is ready for a step test, change the toggle selector switch to the up, "RECORD DATA" position.
6. Select a new position for either the oil or water valve(s); then wait for new steady-state conditions.
7. Repeats steps 2 through 6 as required. Perform the step change sequence as suggested below:

Table 1. Step changes to be performed.

Test	Water valve Position (%)	Oil valve position (%)
01	90-40	90
02	40	90-40
03	40-90	40
04	90	40-90
05	90	90-40
06	90-40	40
07	40	40-90
08	40-90	90
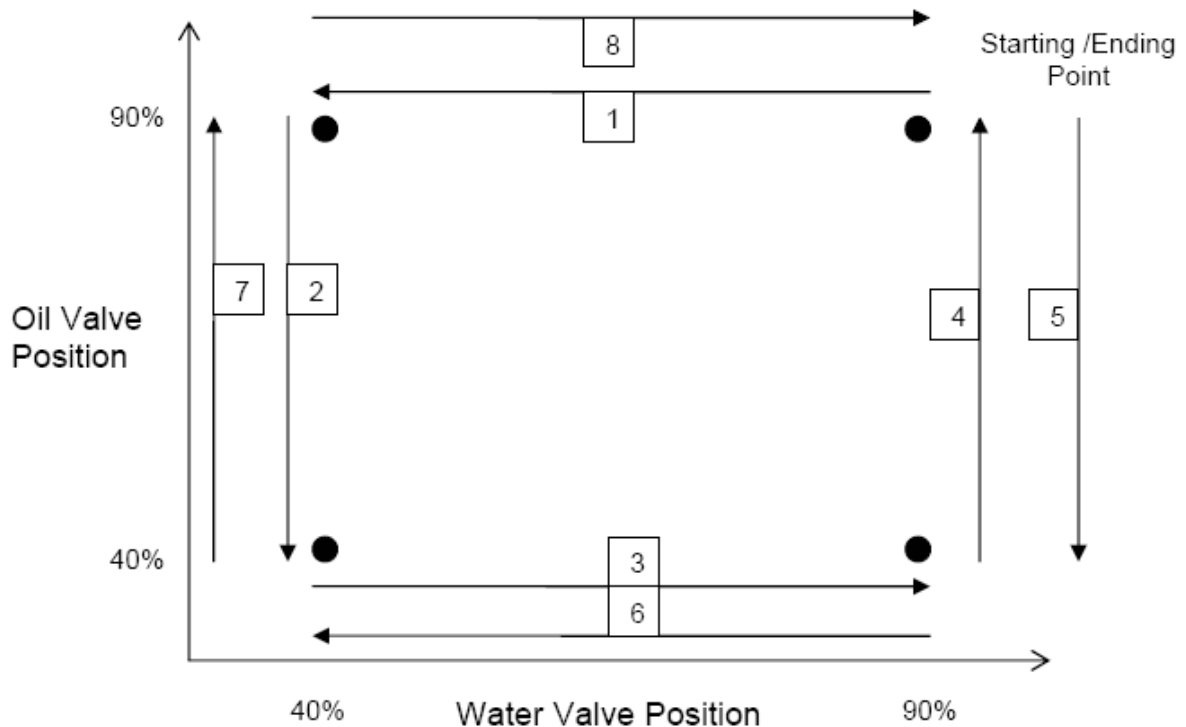
8. Press the STOP button to stop the DPHE.vi program.
9. Once the program has been closed, double check the csv data files for properly recorded content.

After session one but before session two:
- Calculate the transfer functions for the water valve with respect to the oil temperature, the water valve with respect to the water temperature, the oil valve with respect to the water temperature, and the oil valve with respect to the oil temperature.
- Email all the transfer functions to your T.A. **3 days** before start of the second session of the experiment.

Session Two Items - Control Testing:

1. After the DPHE.vi is running, ensure that the CONTROL MODE slider selector switch is the "SESSION 1 System Identification" position.
2. Start with the toggle selector switch in the down, "MONITOR DATA", position.
3. Initiate nominal steady-state conditions by selecting a manual position for both the oil and water valves. The position (percentage of opening) of the valve may be controlled by either the slider bar or by typing in a numerical value.
4. Monitor the process conditions and wait for steady-state conditions.
5. Enter the MPC controller parameters:
    a. The 12 fitting parameters for the 2-by-2 MIMO transfer function matrix for gain, time constant, and time delay (4 each). The engineering units are in either: °C, %, or seconds as applicable.
    b. For constrained operation of the MPC select the upper and lower limits for each valve. Note that the MPC will only function if the current valve positions, when the system switched to automatic control, are both within the constraint limits.
    c. Select the MPC weights for both valves and for both outlet temperatures. These values will be used to scale the relative predicted errors during MPC optimization calculations.
    d. Enter both the prediction horizon and control horizon values.
6. Once the system is ready for a control testing, change the toggle selector switch to the up, "RECORD DATA" position.
7. Switch the CONTROL MODE slider selector switch to the "SESSION 2 Control Testing" position.
8. Select new temperature set points and observe system performance.
9. Repeats steps 1 through 8 as required.
10. Press the STOP button to stop the DPHE.vi program.
11. Once the program has been closed, double check the csv data files for properly recorded content.

More details about this procedure arte given in Appendix A.

Appendix A: Experimental Procedure

Laboratory session 1: system identification

The goal in the first lab session is to obtain process data for the identification of dynamic models of the DPHE process. As shown in Figure 1, four transfer function models that describe the dynamics between the water and oil valve and the oil and water temperature must be identified for this process. To identify each of these models, the students design a series of tests based on step changes on the input variables following a two factorial design. Figure 5 shows a typical design of experiments strategy to be followed by the students. The procedure to perform the step tests is as follows:

1. Start-up of the DPHE process. From the DPHE main console, turn on the main switch that opens the steam valve, the water valve and turns on the oil pump that recycles the oil from DPHE to the oil storage tank.

2. Launch the LabView/MATLAB main program. Set the program to the *systems identification mode* and set the vertical toggle switch for data acquisition in the *monitor data* mode. Selection of Session 1 disables and grays-out the two fluid set-point dials which are forced into manual operation. Set the water valve and the oil valve % of opening to an initial nominal value, e.g. 90% of opening (see Figure 5).

3. With the system at steady-state, set the data acquisition switch to the *record data* mode. This will automatically create a *csv* file that will save the real-time process data. According to the tests designed by the students (Figure 5), step changes are implemented in either the oil or the water valve % of opening. The students will then observe the real-time data displayed on the four dynamic and auto-scaling *x-y* plots of oil valve position, water valve position, oil inlet/outlet temperatures, and water inlet/outlet temperatures (Figure 3).

4. With the system at a new steady-state, return the data acquisition switch to the *monitor data* mode. This action will automatically close the current *csv* file and therefore it will stop recording the real-time process data information for the test performed in step 3. Failure to perform step 4 will cause that all the step tests performed in this session would be saved on the same *csv* file.

5. Repeat steps 3 and 4 for the rest of the identification tests. Once completed, set the data acquisition switch to the *monitor data* mode, set the % of opening of both the oil and the water valve to 90% and let the system cool down until the oil temperature goes below 45°C.

6. Press the *STOP* button from the main LabView/MATLAB program, download the *csv* files that contain the data recorded for each step test performed and turn off the oil pump, the water valve and the steam valve from the main DPHE console.

Laboratory session 2: control testing

For the second laboratory session, the students are asked to submit a pre-lab report containing the following information:

i) The FOPDT process models obtained from the identification test and the agreement between the identified process models and the process data collected in Session 1.

ii) The MPC controller tuning parameters selected for the DPHE process, i.e. the prediction horizon, the control horizon, the input and output weights. These tuning parameters are obtained from simulation of the identified FOPDT models using Simulink$^{(TM)}$.

iii) The relative gain array (RGA) matrix for this system.

To commence the MPC closed-loop control testing, the DPHE is brought to an initial steady-state. This steady-state is achieved by performing steps 1 and 2 of the procedure outlined in the previous section. The DHPE closed-loop tests are performed as follows:

1. While in the *System Identification* mode, input the FOPDT process model parameters, the MPC control parameters and the oil and water valve input limits (process constraints). These parameters are passed into the MATLAB m-script for the configuration of the MPC control.

2. Once the control parameters have been entered, the control mode switch is set to the *Control testing* mode to begin the execution of the MPC control strategy. Upon the transition from the *System Identification* mode to the *Control Testing* mode, the program performs a one-time execution of the process model parameters and MPC parameters to calculate deviation variable values with respect to the current steady-state values.

3. Set the data acquisition button in the *record mode*. Input the values for the oil set point and the water set point (set point test) or keep the current set point values and perform a disturbance in the system (disturbance test). Based on the MPC plant (FOPDT models), the MPC parameters and the requested test, the constrained MPC algorithm is set to minimize the errors between the actual and the desired oil and water temperatures by making changes in the oil and the water valves while satisfying user defined constraints in inputs or/and outputs.

4. Once that the closed-system has reached *a new stea*dy-state, switch to the *monitor data* mode and return to step 3 for a new set point tracking or disturbance rejection test.

5. Once all the closed-loop tests have been completed, change the Session mode switch to the *System Identification* mode and shut down the DPHE process following the procedure outlined in step 6 of the previous section.

Appendix B LabView and MATLAB – An hybrid software interface

The development of the program was divided into 5 sections: initialization, event logic, process control, data recording, and clean-up. Initialization was used to provide default values for the MIMO process model parameters, MPC parameters, HMI mode switches, data-file path, and for supplying reference signals to the two flow control valves. Error-handling was also incorporated into this step. To avoid unnecessary data storage the interface was implemented with two different modes of operation: *i*) monitoring only and *ii*) monitoring and recording. Accordingly, event logic provided exception handling for the change in states of both the *Record* versus *Monitor* mode switch and the *STOP* button. Upon selection of the *Record* mode, a data collection file directory was automatically created. The *csv* file, which name is automatically generated from the system date-time stamp, saves the relevant real-time information acquired from the process and the current parameters defined by the user in the application. Upon selecting *Monitor* or *STOP* events, the program would cause any recorded data in memory to be written into the current *csv* file. The *STOP* event would additionally enable the clean-up portion of the logic. This logic closes the hardware device connections, identifies execution errors, and exits the executable program returning the user to the operating system window. The process control section of the code provides the link between the graphical displays that the students interact with and the variables required for the MATLAB m-script execution.

Monsanto FICHE SIGNALETIQUE MATERIAL SAFETY DATA

| MONSANTO PRODUCT NAME

THERMINOL® 55
HEAT TRANSFER
FLUID | MONSANTO CANADA INC.
2330 ARGENTIA RD.
MISSISSAUGA, ONTARIO
CANADA, L5M 2G4

EMERGENCY PHONE NUMBER
(514) 366-5588   -OR-
Canutec:(613) 996-6666 |

WHMIS CLASSIFICATION

Class D: Poisonous and Infectious Material
          Division 2

PRODUCT IDENTIFICATION

CHEMICAL NAME(S):   Benzene, C_{14-33} alkyl derivatives

SYNONYMS: Light highboiler containing alkylbenzene.
                           alkylindandes, alkylindenes and olefins.

CAS No.:   68855-24-3

TDG HAZARD CLASS: Not Applicable

CDN. SURFACE FREIGHT:
CLASSIFICATION: Heat Transfer Agents or Media, N.O.I.B.N.

TSCA INVENTORY: Components of Therminol© 55 heat transfer
                           fluid appear on the Inventory of Chemical
                           Substances published by the U.S.
                           Environmental Protection Agency (EPA) under
                           authority of the Toxic Substance Control
                           Act (TSCA).

CHEMICAL FAMILY: Alkylated Aromatic

FICHE SIGNALETIQUE
MATERIAL SAFETY DATA

FIRE PROTECTION INFORMATION (CONTINUED)

EXTINGUISHING MEDIA: Water spray, foam, dry chemical, carbon dioxide or any Class B extinguishing agent.

SPECIAL FIREFIGHTING PROCEDURES: Fire fighters and others exposed to vapors or products of combustion should wear full protective clothing including self-contained breathing apparatus. Fire fighting equipment should be thoroughly decontaminated after use.

UNUSUAL FIRE AND EXPLOSION HAZARDS: Hazardous products of decomposition include carbon monoxide, hydrocarbons and oxygenated derivatives.

Therminol® 55 heat transfer fluid is not classified as a fire-resistant heat transfer fluid. Precautions should be taken to avoid exposure to ignition sources in case of spills or leaks of hot liquid. The use of protective devices may be required to minimize fire risk. Consult carrier of fire insurance.

IGNITION TEMPERATURE: 357°C Method: ASTM D-2155

REACTIVITY DATA

STABILITY: Product is stable under ordinary conditions of storage and handling.

HAZARDOUS DECOMPOSITION PRODUCTS: This product will generate carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons and oxygenated derivatives, smoke, and soot when burned.

HAZARDOUS POLYMERIZATION: Does not occur.

HEALTH EFFECTS

The following information presents both human experience and the results of scientific experiments used by qualified experts to assess the effects of Therminol® 55 heat transfer fluid on the health of industrially exposed individuals and to support the Precautionary Statements and Occupational Control Procedures recommended in this document. To avoid misunderstanding, the data provided in this section should be interpreted by individuals trained in evaluation of this type of information.