SCADA System, Stability and Tuning Analysis of Crude Oil in Pipeline Stations: A case study of Nile Blend

Reham Emam DafAllah Ahmed
B.Sc.(Honors) in Chemical Engineering, University of Gezira (2010)

A Dissertation

Submitted to the University of Gezira in Partial Fulfillment of the Requirements for the Award of the Degree of Master of Science in

Chemical Engineering

Department of Applied Chemistry and Chemical Technology

Faculty of Engineering and Technology

June, 2014
SCADA System, Stability And Tuning Analysis of Crude Oil in pipeline stations: A case study of Nile Blend

By

Reham Emam DafAllah Ahmed

Supervision Committee:

<table>
<thead>
<tr>
<th>Name</th>
<th>Position</th>
<th>Signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prof. Gurashi Abdalla Gasmelseed</td>
<td>Major Supervisor</td>
<td>................</td>
</tr>
<tr>
<td>Dr. Salih Mohamed Ahmed Abbaker</td>
<td>Co-supervisor</td>
<td>................</td>
</tr>
</tbody>
</table>

Date of Examination : 26/6/2014
SCADA System, Stability And Tuning Analysis of Crude Oil in pipeline Stations: A case study of Nile Blend

By

Reham Emam DafAllah Ahmed

Examination Committee:

Name                     Position              Signature
Prof. Gurashi Abdalla Gasmelseed   Chairperson       ........
Dr. Hamid Ahmed Mustafa        External Examiner    ........
Dr. Abdalla Mohamed Ahmed Suliman Internal Examiner   ........

Date of Examination :26/6/2014
قالوا سبحانك لا علم لنا إلا ما علمتنا منك إنك أنت العالم الحكيم
صدق الله العظيم
البقرة الآية (32)
DEDECATION

To my mother,
great family,
teachers,
friends
and all those who gave support
ACKNOWLEDGEMENTS

First thanks to my supervisor prof. Gurashi Abdullah Gasmelseed for his patience and help in presenting the various chapter of the research and for his limitless effort and guidance.

I wish to place on record my wholehearted gratitude to my co-supervisor Dr. Salih Mohamed Ahmed Abbaker.

My thankfulness extend to my internal examiner Dr. Abdalla Mohamed Ahmed Suliman.

I express my deep sense of gratitude to my external examiner Dr. Hamid Ahmed Mustafa.

Thanks to Graeter Nile petroleum operation Company GNPOC staff, Sudanese petroleum pipeline company SCADA department staff and Petrodar petroleum operation company staff for all help they have given to me.

And last but not least thanksgiving to all those who encouraged me.
Abstract

Heavy crude oil often has high wax contents. The Nile Blend has a high pour point of 33°C and wax content of 25.87% wt. If crude oil is transported along a pipeline the temperature may dropped and consequently the wax will be deposited on the pipeline wall and may completely block it. Hence it is very important to keep the crude oil above the pour point through either heating or addition of viscosity depressant or both. In this study it is required to control the flow properties of the crude oil along the pipeline, by controlling the temperature and viscosity in stations in series of 300Km apart, where the crude will be transported from the central processing facilities (CPF) to Bashaier at the red sea of 1610 km distance. The objectives of this study were to control the pipeline rheological flow properties through pipeline design, analysis and tuning of control system for temperature and viscosity along the pipeline and connect the local control stations with central SCADA system. The control strategy is developed with two loops, one to control the temperature in the pipeline and the other is to control the viscosity by manipulating the flow quantity of the additives. The control system reported to the SCADA system for more tight control. The control strategy of the system was developed, the transfer functions were identified, stability analysis, tuning and impulse response were performed. A complete control system was designed and connected with SCADA system, the same will be interfaced to digital control with PLC processor. It is recommended to convert controller system to digital controller system. Auto tuning should be done. Fuzzy control might be used for more accuracy and SCADA system is very useful in remote areas, and should be applied.
نظام الإسكادا والاستقرارية والضبط لخام البترول عند محطات خطوط الأنابيب.
(دراسة الحالة: مزيج النيل)
ر. هام إمام دفع الله أحمد
ماجستير العلوم في الهندسة الكيميائية (2014)
قسم الكيمياء التطبيقية وتقنية الكيمياء
جامعة الجزيرة

المستخلص

يحتوي خام البترول الثقيل على نسبة عالية من الشموع. إن مزيج النيل نقله إنسكاب عالية 33٪ ونسبه الشمع 25.78٪ عند نقل الخام عبر الأنابيب تخفض درجه الحرارة مما يؤدي إلى تراكم الشمع في جدران الأنابيب مما يؤدي إلى انسداده بالكامل. لذلك من المهم الحفاظ على الخام فوق نقطة إنسكاب عبر التسخين أو إضافة مخفضات اللزوجة أو الاثنين معًا. في هذه الدراسة يتطلب التحكم في خصائص السريان للأعمال في نقاط التحكم عبر الأنابيب، بالتحكم في الحرارة واللزوجة في المحطات المتتالية على بعد 300 كم حيث يتم التنقل لوحدة المعالجة المركزية إلى بشائر في البحر الأحمر عبر مسافة 1610 كم. إن أهداف هذه الدراسة التحكم في التشوهات الفيزيائية المتعلقة بخصائص السريان لمزيج النيل والتصميم والتحليل والضبط لأنظمة التحكم للحرارة واللزوجة عبر الأنابيب وربط المحطات المحلية بنظام الإسكادا. طُورت إستراتيجية التحكم بحلقتين، الأول هو التحكم في الحرارة والثاني هو التحكم في اللزوجة عبر التحكم في كمية الإضافات. يقوم نظام التحكم بإرسال البيانات لنظام الإسكادا لضبط نظم التحكم. طُورت إستراتيجية التحكم، عُرفت بـ نظام الاستقرارية، وقدمت مراقبة وتقييم الضبط وإستجابة الدفع. صُمّم نظام التحكم الكامل وربط مع نظام الإسكادا ونظام التحكم الرقمي مع نظام التحكم البرمجي المنطقي. توصى الدراسة بأن يحول نظام التحكم إلى نظام رقمي ويستخدم الضبط الآلي وتطبيق نظام الفوزيتكترول لضخ الزيت. ويطبق نظام الإسكادا في المناطق البعيدة.
# Table of Content

<table>
<thead>
<tr>
<th>Title</th>
<th>Page number</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEDICATION</td>
<td>I</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>II</td>
</tr>
<tr>
<td>Abstract English</td>
<td>III</td>
</tr>
<tr>
<td>Abstract Arabic</td>
<td>IV</td>
</tr>
<tr>
<td>List of Content</td>
<td>V</td>
</tr>
<tr>
<td>List of Tables</td>
<td>X</td>
</tr>
<tr>
<td>List of Figures</td>
<td>XI</td>
</tr>
<tr>
<td>List of Photographs</td>
<td>XII</td>
</tr>
<tr>
<td>List of Abbreviations</td>
<td>XIII</td>
</tr>
<tr>
<td>List of Nomenclature</td>
<td>XIV</td>
</tr>
</tbody>
</table>

## Chapter One

### Introduction

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 General introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Crude oil pour point</td>
<td>2</td>
</tr>
<tr>
<td>1.3 Viscosity of crude oils</td>
<td>2</td>
</tr>
<tr>
<td>1.4 Pour Point Depressant (PPD)</td>
<td>3</td>
</tr>
<tr>
<td>1.5 Treatment of the wax deposition</td>
<td>3</td>
</tr>
<tr>
<td>1.6 Types of processes</td>
<td>3</td>
</tr>
<tr>
<td>1.6.1 Thermal process</td>
<td>4</td>
</tr>
<tr>
<td>1.6.2 Thermal cycles process</td>
<td>4</td>
</tr>
<tr>
<td>1.6.3 The combination process</td>
<td>4</td>
</tr>
<tr>
<td>1.7 Nile blend properties and problems</td>
<td>4</td>
</tr>
<tr>
<td>1.8 Type of controllers</td>
<td>5</td>
</tr>
<tr>
<td>1.8.1 Proportional control</td>
<td>5</td>
</tr>
<tr>
<td>1.8.2 Proportional Integral (PI) control</td>
<td>5</td>
</tr>
<tr>
<td>1.8.3 Proportional plus Integral plus Derivative (PID) control.</td>
<td>5</td>
</tr>
<tr>
<td>Objectives</td>
<td>6</td>
</tr>
</tbody>
</table>

## Chapter Two

### Literature Review

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Well treatment</td>
<td>7</td>
</tr>
<tr>
<td>2.1.1 Adding pour point depressant PPD</td>
<td>7</td>
</tr>
<tr>
<td>2.1.2 Water treatment</td>
<td>7</td>
</tr>
<tr>
<td>2.1.3 Field processing facility treatment (FPF)</td>
<td>7</td>
</tr>
<tr>
<td>2.1.4 Central processing facility treatment CPF</td>
<td>7</td>
</tr>
<tr>
<td>2.1.5 Electrostatic treaters</td>
<td>7</td>
</tr>
<tr>
<td>2.1.6 Gas boot</td>
<td>8</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>2.1.7</td>
<td>Oil recycling pumps</td>
</tr>
<tr>
<td>2.1.8</td>
<td>Crude storage tank</td>
</tr>
<tr>
<td>2.1.9</td>
<td>Sales oil heater</td>
</tr>
<tr>
<td>2.1.10</td>
<td>Pipeline Operation</td>
</tr>
<tr>
<td>2.1.10.1</td>
<td>Pipeline</td>
</tr>
<tr>
<td>2.1.10.2</td>
<td>Scope</td>
</tr>
<tr>
<td>2.1.10.3</td>
<td>Overview</td>
</tr>
<tr>
<td>2.1.11</td>
<td>Waxy crude oil</td>
</tr>
<tr>
<td>2.1.12</td>
<td>Control of paraffin wax related problem</td>
</tr>
<tr>
<td>2.1.13</td>
<td>Previous studies of Sudan crude oil</td>
</tr>
<tr>
<td>2.1.14</td>
<td>Paraffin Control</td>
</tr>
<tr>
<td>2.1.14.1</td>
<td>Paraffin deposition</td>
</tr>
<tr>
<td>2.1.14.2</td>
<td>Paraffin removal</td>
</tr>
<tr>
<td>2.1.15</td>
<td>Field Application of chemical flow improvers in pipeline.</td>
</tr>
<tr>
<td>2.1.15.1</td>
<td>Chemical application</td>
</tr>
<tr>
<td>2.1.15.2</td>
<td>Comparison of Methods for the Flow Improvement of Paraffinic Crude</td>
</tr>
<tr>
<td>2.1.15.3</td>
<td>Dilution with Hydrocarbons</td>
</tr>
<tr>
<td>2.1.15.4</td>
<td>Thermal Methods</td>
</tr>
<tr>
<td>2.1.15.5</td>
<td>Magnetic and Electromagnetic methods</td>
</tr>
<tr>
<td>2.1.15.6</td>
<td>Microbial methods</td>
</tr>
<tr>
<td>2.1.15.7</td>
<td>Chemical methods</td>
</tr>
<tr>
<td>2.1.16</td>
<td>Criteria for the selection of paraffin Inhibitors</td>
</tr>
<tr>
<td>2.1.17</td>
<td>Chemical control techniques for the paraffin deposition</td>
</tr>
<tr>
<td>2.1.18</td>
<td>Control Systems</td>
</tr>
<tr>
<td>2.1.18.1</td>
<td>Systems</td>
</tr>
<tr>
<td>2.1.18.2</td>
<td>Control Classification</td>
</tr>
<tr>
<td>A.</td>
<td>Manual control</td>
</tr>
<tr>
<td>B.</td>
<td>Automatic control</td>
</tr>
<tr>
<td>2.1.18.3</td>
<td>Open-loop Control</td>
</tr>
<tr>
<td>2.1.18.4</td>
<td>Closed-loop Control</td>
</tr>
<tr>
<td>2.1.19</td>
<td>Analog and Digital Controllers</td>
</tr>
<tr>
<td>2.2</td>
<td>Pipeline Leak Detection Systems</td>
</tr>
<tr>
<td>2.2.11</td>
<td>Externally based methods</td>
</tr>
<tr>
<td>2.2.2</td>
<td>Internally based methods</td>
</tr>
<tr>
<td>2.3</td>
<td>Major components of a computer-based LDS</td>
</tr>
<tr>
<td>2.3.1</td>
<td>Instrumentation</td>
</tr>
<tr>
<td>2.4</td>
<td>SCADA Communications</td>
</tr>
<tr>
<td>2.4.1</td>
<td>SCADA benefits</td>
</tr>
<tr>
<td>2.4.2 SCADA system consists of</td>
<td>24</td>
</tr>
<tr>
<td>2.4.3 Field data interface devices</td>
<td>25</td>
</tr>
<tr>
<td>2.4.4 Remote terminal unit (RTU):</td>
<td>25</td>
</tr>
<tr>
<td>2.4.5 Central Host Computer</td>
<td>25</td>
</tr>
<tr>
<td>2.4.6 HMI/MMI (HUMAN MACHINE INTERFACE/MAN MACHINE INTERFACE):</td>
<td>26</td>
</tr>
<tr>
<td>2.5 INTERNAL LEAK DETECTION SYTEMS</td>
<td>26</td>
</tr>
<tr>
<td>2.6 EXTERNAL LEAK DETECTION SYSTEMS</td>
<td>26</td>
</tr>
<tr>
<td>2.6.1 Acoustic Emissions</td>
<td>26</td>
</tr>
<tr>
<td>2.6.2 Fiber Optic Sensing</td>
<td>27</td>
</tr>
<tr>
<td>2.6.3 Digital controller</td>
<td>27</td>
</tr>
</tbody>
</table>

**Chapter three**

<table>
<thead>
<tr>
<th>Material and method</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 Introduction</td>
<td>28</td>
</tr>
<tr>
<td>3.2 Sensors and measuring devices</td>
<td>28</td>
</tr>
<tr>
<td>3.2.1 Type of controllers</td>
<td>29</td>
</tr>
<tr>
<td>3.2.2 Analog VS Digital</td>
<td>30</td>
</tr>
<tr>
<td>3.2.3 Selecting of the Controller Transfer Function</td>
<td>30</td>
</tr>
<tr>
<td>3.2.4 Modeling of the system</td>
<td>30</td>
</tr>
<tr>
<td>3.2.5 Dynamic of the system</td>
<td>30</td>
</tr>
<tr>
<td>3.2.6 Transfer Function representation</td>
<td>31</td>
</tr>
<tr>
<td>3.2.7 System stability and tuning</td>
<td>31</td>
</tr>
<tr>
<td>3.2.8 Stability</td>
<td>32</td>
</tr>
<tr>
<td>3.2.9 Stability test</td>
<td>32</td>
</tr>
<tr>
<td>3.2.10 Routh’s Criterion</td>
<td>33</td>
</tr>
<tr>
<td>3.2.11 Direct Substitution Analysis</td>
<td>33</td>
</tr>
<tr>
<td>3.3.12 Root locus analysis</td>
<td>33</td>
</tr>
<tr>
<td>3.2.13 Bode Plots</td>
<td>35</td>
</tr>
<tr>
<td>3.2.14 Tuning controllers</td>
<td>36</td>
</tr>
<tr>
<td>3.2.15 Ziegler – Nichols Tuning Technique:</td>
<td>36</td>
</tr>
<tr>
<td>3.2.16 Time Response</td>
<td>37</td>
</tr>
<tr>
<td>3.2.17 MATLAB Software</td>
<td>37</td>
</tr>
<tr>
<td>3.2.18 Digital Control Design for Proportional Integral Derivative (PID) control</td>
<td>37</td>
</tr>
</tbody>
</table>

**Chapter four**

<p>| Result and Discussion | 37 |</p>
<table>
<thead>
<tr>
<th>4.1.1 Introduction</th>
<th>38</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1.2 Control Strategy:</td>
<td>38</td>
</tr>
<tr>
<td>4.1.3 Control loops configuration:</td>
<td>38</td>
</tr>
<tr>
<td>4.1.4 The controller transfer function ((G_c))</td>
<td>39</td>
</tr>
<tr>
<td>4.1.5 Identification of transfer functions</td>
<td>40</td>
</tr>
<tr>
<td>4.1.6 Transfer function of the valve</td>
<td>40</td>
</tr>
<tr>
<td>4.1.7 Dynamics of the thermocouple for temp measurement</td>
<td>41</td>
</tr>
<tr>
<td>4.1.7.1.1 Transfer function of the heat exchanger</td>
<td>42</td>
</tr>
<tr>
<td>4.1.7.1.2 Transfer function of the composition</td>
<td>43</td>
</tr>
<tr>
<td>4.1.8 Controller stability</td>
<td>44</td>
</tr>
<tr>
<td>4.2 Analysis and optimum settings for Loop1 (heat exchanger).</td>
<td>46</td>
</tr>
<tr>
<td>4.2.1 Routh _Hurwitz Method</td>
<td>46</td>
</tr>
<tr>
<td>4.2.2 Direct substitution method</td>
<td>47</td>
</tr>
<tr>
<td>4.2.3 Determination of adjustable parameters, these are determined using Z-N.</td>
<td>48</td>
</tr>
<tr>
<td>4.2.4 Offset investigation</td>
<td>49</td>
</tr>
<tr>
<td>4.2.5 Impulse response of a system</td>
<td>50</td>
</tr>
<tr>
<td>4.2.6.1 Determination of the adjustable parameters, these are determined using Z-N.</td>
<td>51</td>
</tr>
<tr>
<td>4.2.6.2 Offset investigation</td>
<td>52</td>
</tr>
<tr>
<td>4.2.6.3 Response</td>
<td>53</td>
</tr>
<tr>
<td>4.2.6.4 Response of PI &amp;PID controller by Root locous for loop1:</td>
<td>53</td>
</tr>
<tr>
<td>4.2.7 Bode methods</td>
<td>55</td>
</tr>
<tr>
<td>4.2.7.1 Determination of the adjustable parameters, these are determined using Z-N.</td>
<td>56</td>
</tr>
<tr>
<td>4.2.7.2 Offset investigation:</td>
<td>57</td>
</tr>
<tr>
<td>4.2.8 Response of Bode:</td>
<td>58</td>
</tr>
<tr>
<td>4.3 Analysis and optimum settings for Loop2 (composition).</td>
<td>59</td>
</tr>
<tr>
<td>4.3.1 Routh Hurwitz Method:</td>
<td>59</td>
</tr>
<tr>
<td>4.3.2 Direct substitution method</td>
<td>60</td>
</tr>
<tr>
<td>4.3.3 Determination of the adjustable parameters, using Z-N.</td>
<td>60</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Fig.(2.1) Digital control system .......................................................... 19
Fig.(3.1): Flow diagram of research methodology .................................. 31
Fig. (3.2): Root Locus ........................................................................ 34
Fig. (3.3): Bode plot ........................................................................ 35
Fig. (4.1): Physical diagram for Temperature and viscosity control loop .. 39
Fig. (4.2): Penumatic valve ................................................................. 40
Fig. (4.3): Heat exchanger control loop ............................................. 45
Fig. (4.4): Step response of closed loop transfer function for proportional controller by Routh Hurwitz adjustable controller parameters. .................................................. 50
Fig. (4.5): Root Locus plot ................................................................. 51
Fig. (4.6): Response of Root Locus .................................................... 53
Fig. (4.7): Impulse response of PI by Root Locus .................................. 54
Fig. (4.8): Impulse response of PID by Root Locus .............................. 54
Fig. (4.9): Bode plot ........................................................................ 55
Fig. (4.10): Response of Bode ............................................................ 58
Fig. (4.11): Composition control loop ................................................ 58
Fig. (4.12): Response of Routh Array parameters in loop2 .................... 62
Fig. (4.13): Root locus plot ............................................................... 63
Fig. (4.14): Response of P controller using Root locus ....................... 65
Fig. (4.15): Impulse response of PI controller using Root locus .......... 66
Fig. (4.16): Response of PID controller using Root locus ................... 67
Fig. (4.17): Bode plot ..................................................................... 67
Fig. (4.19): Response of Bode plot .................................................... 70
Fig. (4.20): SCADA control loop ...................................................... 73
Fig. (4.21): Digital temperature controller ....................................... 74
Fig. (4.22): Digital temperature controller connected with SCADA system. ......................................................... 75
List of Tables

Table (2.1): Properties of Nile blend
Table (3.1): Typical measuring devices for process control
Table (3.2): Ziegler-Nichols adjustable parameters
Table (4.1): Ziegler-Nichols adjustable controller parameters for heat exchanger control loop for Routh-Hurwitz
Table (4.2): Ziegler-Nichols adjustable controller parameters for heat exchanger control loop for Root Locus
Table (4.3): Ziegler-Nichols adjustable controller parameters for heat exchanger control loop for Bode
Table (4.4): Ziegler-Nichols adjustable controller parameters for composition control loop for Routh
Table (4.5): Ziegler-Nichols adjustable controller parameters for composition control loop for Root Locus
Table (4.6): Ziegler-Nichols adjustable controller parameters for composition control loop for Bode
Table (4.7): Comparison between the adjustable parameter using different method of tuning for heat exchanger control loop 1
Table (4.8): Comparison between the adjustable parameter using different method of tuning for composition control loop 2
Table (4.9): Comparison between the offset investigations using different method of tuning loop 1
Table (4.10): Comparison between the offset investigations using different method of tuning loop 2
Table (4.11): Comparison between the three type of controller by Root Locus loop 1
Table (4.12): Comparison between the three type of controller by Root Locus loop 2
List of Photographs

Photograph(2.3): SCADAPack(RTU) ........................................................................................................... 2
2
Photograph(2.4): SCADARTU ...................................................................................................................... 24
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPD</td>
<td>Pour Point Depressant</td>
</tr>
<tr>
<td>CPF</td>
<td>Central Process Facilities</td>
</tr>
<tr>
<td>FPF</td>
<td>Field Process Facilities</td>
</tr>
<tr>
<td>BMT</td>
<td>Bashayer Marine Terminal</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable Logic Controllers</td>
</tr>
<tr>
<td>MTU</td>
<td>Master Terminal Unit</td>
</tr>
<tr>
<td>LDS</td>
<td>Leak detection system</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory Control and Data Acquisition</td>
</tr>
<tr>
<td>API</td>
<td>American Petroleum Institute</td>
</tr>
<tr>
<td>HMI</td>
<td>Human Machine Interface software or</td>
</tr>
<tr>
<td>MMI</td>
<td>Man Machine Interface</td>
</tr>
<tr>
<td>CPM</td>
<td>Computational Pipeline Monitoring</td>
</tr>
<tr>
<td>P</td>
<td>Proportional Controller</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional Integral Controller</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional plus Integral plus Derivative controller.</td>
</tr>
<tr>
<td>ZOH</td>
<td>Zero-order hold</td>
</tr>
<tr>
<td>A/D</td>
<td>Analog-to-Digital</td>
</tr>
<tr>
<td>D/A</td>
<td>Digital-to-Analog</td>
</tr>
<tr>
<td>LHP</td>
<td>left half plane</td>
</tr>
</tbody>
</table>
NOMENCLATURE

\( K_c \) Proportional controller gain.

\( K_u \) Ultimate gain

\( P_u \) Ultimate period

\( \tau_i \) The integration time

\( \tau_d \) The deviation time

\( PA \) Force exerted by the compressed air at the top of the diaphragm.

\( KX \) Force exerted by the spring, hookes low.

\( C \frac{dx}{dt} \) Fractional forces exerted up word and resulting from close contact of the steam with the valve packing.

\( Y \) Temp to be read by the thermocouple.

\( \theta \) The surrounding temp.

\( H \) Heat transfer coefficient.

\( A \) Heat transfer area.

\( M \) Mass of the joint of thermocouple.

\( cp \) Specific heat.

\( F_0 C_{A_0} \) Flow of A into the system.

\( FC_A \) Flow of A out of the system.

\( \frac{d}{dt} (vC_A) \) The rate of change of A inside the tank.

\( G_c \) The controller transfer function

\( G_p \) Process transfer function.

\( G_v \) The valve transfer function.

\( G_m \) Measurement transfer function

\( Q_s \) Process output

\( \omega_{co} \) Crossover frequency.
$C_{(s)}$: Laplace transform of controlled output $C_{(t)}$

$\otimes$: Summing point symbol, used to denote algebraic summation
Chapter One

Introduction

Nature of petroleum

1.1 General introduction

Petroleum is defined as a natural organic material composed principally of hydrocarbons, which occurs in gaseous or liquid state in geological traps[1]. Crude oils have physical and chemical characteristics that vary widely from one production field to another and even within the same field. The roughest from of characterization, but nevertheless one that has great economic consequence is the classification of “light” and “heavy” crude. Because crude is composed essentially of hydrocarbon molecules, its specific gravity varies with its H/C atomic ratio. Specific gravities for various crude oils will range from 0.7 to 1.0; they are often expressed in degree API (American Petroleum Institute) which will vary between 70 and 5, it is clear that this variable gravity reflects composition of chemical families that are very different from each other[1].

The oil industry classifies “crude” oil by where it was produced or its origin and often by its relative weight (API gravity or viscosity (“light”, “intermediate” or” heavy”); in addition it may also be referred to as “sweet” (it contains relatively little sulfur), or as “sour” (it contains substantial amounts of sulfur) and requires more refining in order to meet current petroleum specifications. The crude oil in the Sudan called NILE BLEND is waxy in nature and has a higher viscosity, medium density, low sulphur content, low metal content and lower pour point at temperature higher than the ambient temperature. At a low temperature the transportation of the crude oil may be difficult as a result of the pour point of the crude oil, so we have to keep the oil temperature higher than this pour point to decrease the viscosity and increase the flow rate of the oil. The crude oil have disadvantage which is the wax may sediment in the pipeline wall, this will reduce the effective diameter of the pipe and cause problems during pigging.

Pipelines are used to reach the end user markets to satisfy their increasing demand of different types of fuels. Transportation by pipelines is considered the most economical on
land mode, good efficiency, reliability of continuity, safety and less harm to the environment and nature. The advantage of pipelines are:

1. It’s easy maintenance and repairs.
2. Its readiness to be fully automated and controlled.
3. Improving economical indexes.[2].

1.2 Crude oil pour point

Pour point is the lowest temperature at which crude oil can flow through the pipeline without any problem. The pour point value depends on crude oil gel point. When the wax molecules loose moisture the crude oil becomes elastic jell. When crude petroleum is cooled, there is no distinct change from liquid to solid as is the case for pure substances. First there is a more or less noticeable change in viscosity, then, if the temperature is lowered sufficiently, the crude oil ceases to be fluid, and approaches the solid state, by thickening. This happens because the crude oil is a complex mixture in which the majority of components do not generally crystallize; their transition to the solid state does not therefore occur at a constant temperature, but rather along a temperature range, for which the parameters are a function of the crude oils and previous treatment.

Knowledge of the crude’s previous history is very important. Preheating 45°C _65°C lowers the temperature of the pour point because the crude petroleum contains seeds of paraffinic crystals, and these are destroyed during preheating. If the crude is preheated to a higher temperature (about 100°C), an increase in pour point is observed which is due to the vaporization of light hydrocarbons, is the crude becoming heavier. The pour point of crude oils is measured to give an approximate indication as their pumpability. In fact, the agitation of the fluid brought on by pumping can stop, slow down or destroy the formation of crystals[1].

1.3 Viscosity of crude oils

Viscosity is the resistance which occurs between the layers of the crude oil during the pumping process. This resistance depends on the molecules volume, length of hydrocarbon chains, the speeds among the molecules and the form of wax matrix. There is a difference between pour point valve and viscosity. The pour point depends on gel point, but viscosity
depends on resistant force between the crude oil molecules and layers and through the pumping process.

The measurement of crude oils viscosity at different temperatures is particularly important to the calculation of the pressure drop in pipelines and refinery piping systems, as well as for the specification of pumps and exchangers. The change in viscosity with temperature is not the same for all crudes. The viscosity of a paraffinic crude increases rapidly with decreasing temperature; on the other hand, for the naphthenic crudes, the increase in viscosity is more gradual [1].

1.4 Pour Point Depressant (PPD)

PPD is an emulsifying agent injected into the crude oil to control the wax. It consists of four or more of the following polymers:

- Alpha olefin copolymer
- Polyester
- Phosphate ester
- Solvent
- Surfactant
- Dispersant

The main objective of PPDs is retarding the wax appearance in the crude oil by modifying the wax molecules. This helps to reduce the pour point value and viscosity in central process facilities (CPF).

1.5 Treatment of the wax deposition

The problem of wax deposition could be solved by various methods such as; heating process, blending process, PPD injection or combination of some of these processes. The mechanism of heating process is melting the wax molecules. The mechanism of blending process is dissolving the wax molecules. And the mechanism of PPDs is modification of the wax molecules. The crude oil is heated in CPF by a chemical called thermenoul. The PPDs is injected into the crude oil in different doses (50ppm, 100ppm, 150ppm, 200ppm). In the blending process the crude oil is blended by light hydrocarbons (gasoline, gas oil, kerosene, naphtha and diesel). Therefore one must take into consideration the other factors
which affect these processes (the quenching process, mode of cooling, cooling rate, the ambient temperature and the length of heating time).

1.6 Types of processes

1.7 Thermal process

In thermal process the crude oil is heated to different temperatures (70°C, 80°C, 90°C, 100°C). The crude oil was quenched to 40°C. The quenching process helps in the arrangement of the wax molecules in an ideal form. When the crude oil is heated to 90°C and 100°C the pour point value and viscosity is decreased. So before pumping the crude oil through the pipeline one must study all factors which affect the pour point value and viscosity. From investigation one could determine the ideal temperature to which the crude oil should be heated.

1.7.1 Thermal cycles process

In thermal cycles process the crude oil is heated to 90°C and quenched to 40°C in various thermal cycles. When the crude oil is pumped from field process facilities (FPF) to central process facilities (CPF) its temperature is 40°C. The change which takes place in cycles number, leads to different values of viscosity. In the design of the thermal cycle process one must take into consideration all factors in the characteristics Rheology of the crude oil.

1.7.2 The combination process

The combination process is designed by various numbers of thermal cycles combined with the injection of PPD in different ways. The role of this process is to reduce the pour point value and viscosity, by wax molecules rearrangement, and modifying wax behavior.

1.7.3 Nile blend properties and problems

Nile blend properties differ due to the various production fields. The main features of the blend mixture are: medium density, sweet (low sulphur content), low metal content. The crude is viscous and relatively low pour point at temperatures higher than the ambient temperature. Nile blend may experience wax deposition problems throughout the pipeline system. Sliding may occur in the storage tanks and the high level of insoluble wax, also indicates potential for pipeline pumpability problems. However, pumpability issues must be determined by viscosity measurements, as the crude oil rheology is very sensitive to temperature, time and
shear. For Nile blend crude, both heat and chemical treatment are used (wax crystal modifiers). These are more effective and economic and thereby influence the rheology of crude.

1.8 Type of controllers

Process control is the measurement of a process variable, the comparison of that variable with its respective set point, and the manipulation of the process in a way that will hold the variable at its set point when the set point changes or when a disturbance changes the process[26].

One way to improve the step response of a control system is to add a controller to the feedback control system, the closed loop systems can be controlled by Proportional control, Proportional Integral(PI) control and Proportional plus Integral plus Derivative (PID) control.

1.8.1 Proportional control

The proportional action is responds quickly to changes in error deviation, However the proportion controller does not guarantee a zero steady-state control error. The proportional controller is consider to be simple controller which is the best and can be used when nonzero steady state error is acceptable or if the controlled system contain pure integrator. Generally, it used in pressure control or level control[27].

1.8.2 Proportional Integral(PI) control

The reset (or integral) contribution from more mathematical point of view, At any time he rate of change of the output is the gain time the reset rate times the error is acceptable or if the controlled system contains pure integrator. Generally, it used in pressure control or level control[28].

1.8.3 Proportional plus Integral plus Derivative (PID) control.

The PID control algorithm is made of three basic responses, Proportional (or gain), integral (or reset), and derivative[26].

Derivative is the third and final element of PID control. Derivative responds to the rate of change of the process (or error). Derivative is the normally applied to the process only.
Analog PID controllers are common in many applications. They can be easily constructed using analog devices such as operational amplifiers, capacitors and resistors. They are reliable in mechanical feedback systems and able to satisfy many control problems.

Objectives:

1. To control the crude oil rheological flow properties through pipeline.
2. To design, analysis and tuning of control system for temperature and viscosity along the pipeline.
3. To connect the local control stations with central SCADA system.
Chapter Two

Literature Review

Nile blend field treatment

2.1 Well treatment

2.1.1 Adding pour point depressant PPD

The pour point depressant (PPD) is pumped from storage tank (near the well), to the pipeline. Determining of pour point depressant dosage depends on well properties. This procedure has been done for Toma south, Eltoor and Elnar fields because these fields have high wax content.

2.1.2 Water treatment

Some fields have high water content so demulsifiers are added to remove the water content (Heglig field).

2.1.3 Field processing facility treatment (FPF)

The unit where the first treatment of the crude oil, when crude pumped from wells to (FPF). At the FPF, the crude oil is heated to 85 °C and treatment dosage of pour point depressant is added to decrease the viscosity and pour point. All these treatments are used to improve the crude properties and to ensure its flow to central processing facilities CPF.

2.1.4 Central processing facility treatment CPF

In this unit the production of each field is collected and the separation of water, gas and addition of PPD take place. Therefore the process of wax inhibitors is determined by designed ideal pumping process.

2.1.5 Electrostatic treaters

It is horizontal vessel containing two electrodes; the designed temperature and pressure are (115 °C and 1034 k Pa respectively). After injection of demulsifiers at 85 the crude is transferred through pipe to electrostatic treaties, with the action of electrostatic field and specific gravity molecules of water are separated from the crude and settle in the lower part of the vessel (pressure inside the vessel is 69kPa to obstruct the release of gases from the crude).
2.1.6 Gas boot

This is a vertical cylinder of height 7.5 m and a diameter of 3 m and it is used to remove gases.

2.1.7 Oil recycling pumps

After leaving gas boots, the crude is pumped into oil heaters. Oil heaters are heat exchangers which increase the temperature of crude to 105 by means of crossed heat exchangers. The crude is pumped to treaters for heat exchange with other fields crude, and then the crude temperature decreased to (65°C -70°C).

2.1.8 Crude storage tank

The maximum capacity of storage tank is (300.000 bpl,4769 m3). The tank bottom and wells (up to 1.2 m) are coated with an oil resistant epoxy to prevent corrosion; each tank is supplied with heating coil to sustain temperature at (40°C -60°C).

2.1.9 Sales oil heater

After oil is treated in electrostatic treaters and gas boots, the crude oil is heated by thermonol. This treated crude called sales oil, and then it was pumped into heat exchangers, to be exchanged with untreated crude which comes from others (FPF).
Table (2.1): Properties of Nile blend[6].

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt Content</td>
<td>ASTM D 3230</td>
<td>mgNaCl/L</td>
<td>9.12</td>
</tr>
<tr>
<td>Density at 15°C</td>
<td>ASTM D 5002</td>
<td>kg/m³</td>
<td>850.4</td>
</tr>
<tr>
<td>Wax Content</td>
<td>UOP 46</td>
<td>wt%</td>
<td>25.87</td>
</tr>
<tr>
<td>Flash Point</td>
<td>IP 170</td>
<td>°C</td>
<td>21.5</td>
</tr>
<tr>
<td>Pour Point</td>
<td>ASTM D 97</td>
<td>°C</td>
<td>33.0</td>
</tr>
<tr>
<td>Kinematic Viscosity at 50°C</td>
<td>ASTM D 445</td>
<td>mm²/s</td>
<td>22.64</td>
</tr>
<tr>
<td>Kinematic Viscosity at 80°C</td>
<td>ASTM D 445</td>
<td>mm²/s</td>
<td>8.884</td>
</tr>
<tr>
<td>Water Content by Distillation</td>
<td>ASTM D 4006</td>
<td>v%</td>
<td>0.09</td>
</tr>
<tr>
<td>Ash content</td>
<td>ASTM D 482</td>
<td>wt%</td>
<td>0.043</td>
</tr>
<tr>
<td>Asphaltene Content</td>
<td>IP 143</td>
<td>wt%</td>
<td>0.11</td>
</tr>
<tr>
<td>Sulfur Content</td>
<td>ASTM D 4294</td>
<td>wt%</td>
<td>0.051</td>
</tr>
</tbody>
</table>

2.1.10 Pipeline Operation

2.1.10.1 Pipeline:
Is a transportation of goods through a pipeline. There for gases and liquids, any chemically stable substance can be sent through a pipeline. Often these pipelines are inspected and cleaned using pipeline inspection gauges “pigs”

2.1.10.2 Scope
Any oil development project consists of the following facilities:

- Upstream Facilities:
  - Flow lines
  - Centralized Processing Facilities(CPF)
- Power Stations
- Power transmission lines

- Downstream Facilities
  - Field Pipeline
  - Export Pipeline from CPF to port sedan Marine Terminal
  - Pumping Facilities
  - SCADA and Telecommunication System
  - Export Marine Terminal, located at port sudan

### 2.1.10.3 Overview

The pipeline and pump stations integrated system is split into two sections:

- The first section, termed the “field pipeline”, linked the Field Process facilities (FPF) to the Central Process Facilities (CPF).
- The second section, called the “Export Pipeline”, links the CPF to a new Marine Terminal near port sudan.

PS1 is located at FPF. The crude oil from FPF still retains water emulsion mixture in the field pipeline facilities (FPF), in order to reduce pour point from 43°C to 36°C; pour point depressant (PPD) injection and heat treatment are carried out, before the crude oil enters into the station PS1. At CPF, the crude is further treated to achieve 0.5% max BSW (Basic Sediment Water) and the chemical PPD is injected, the expected pour point of treated crude oil for export is 36°C for lower viscosity.

### 2.1.11 Waxy crude oil

The majority of wax crude oil if not all, contains a proportion of petroleum waxes. The concentration, structure and molecular weight range of these waxes vary considerably from one crude oil source to another. Since their boiling also differ, certain waxes occur and indeed concentrate, in different distillate fractions. The trending of the wax to precipitate and crystallize as the oil cools during production, transportation and storage, or even subsequent use gives rise to a variety of problems.


2.1.12 Control of paraffin wax related problem

Complete elimination of problems related to crystallization of pour point during crude oil produced, by the obvious method of heating pipelines, storage, vessels etc. is clearly not often economically viable. However variety of other techniques for the control of such problems do exist so that at least they become manageable and the wax, and therefore the problem, is transferred to downstream operations and or products where they may perhaps be more conveniently treated [3].

2.1.13 Previous studies of Sudan crude oil

The oil was found to be highly non-Newtonian below approximately 40 °C, accompanied by the very sudden increase in viscosity which was attributed to presence of the wax crystals, and their interactions (crystallization of n-alkenes) once the temperature dropped below the non-Newtonian limit, every aspect of oils treatment becomes a part of the oils history[4].

Wax agglomerations which have been chopped up during transit through the pump stations, increase the quantity of nucleating sites to distributed within the blend, which cause the blend revert its higher pour point condition [5].

The pour point difference reported at Heglig and B.M.T is an indication that the cemically treated blend received at B.M.T, has reverted to its original condition after having undergoing a prolonged pipeline process over one month [6].

The pour point of crude received in Bashayer Marine Terminal (BMT), has increased from 27°C to 33°C and has further increased to 36°C. changing pour point clearly demonstrates that the most improved properties of crude got in CPF have been lost. The potential factors that may affect the pour point listed previously were thermal cycling at different location and destruction of pour point depressant. This only leaves shearing of wax agglomerations during transit through the pump stations as the probable cause of pour point problem[7].

The upper point of the export oil has increased since field start up from 24 towards 36. They attributed this as a direct result of changing the composition of the export oil from predominantly low wax content oils from Heglig and unity fields at the startup of production, to an export mixture dominated by high wax content oils from El Nar, Toma South and El
Toor fields. Due to the use of pour point depressant the lower pour point results reported at Heglig have not reflected compositional changes, and so have not raised the awareness of potential problems for the downstream system. Thermal cycling during transportation either due to elevation changes or from heating during pumping should be also considered. Furthermore, the pour point depressant could be destroyed by the high shear rate imposed during transit through the pipeline pump stations[8].

The spread between the upper and lower pour point results should be considered as a key indicator of potential problems if the oil is poorly beneficiated. Originally the spread between the upper and lower pour point was only 3 on daily basis, but this has risen to 9 and 12 since the composition of the export oil has changed towards the more paraffinic oils[8].

Due to high wax content of Nile Blend and the reversion to upper pour point condition along with relatively low submarine temperature, the submarine pipeline is going to be faced with two problems, one is wax deposition and another is restart[6].

Analysis of Nile Blend suggest that there is a very slight tendency for very small quantities of higher molecular weight paraffins and asphaltenes to drop out of solutions and deposit on pipeline walls[7].

A-heptanes in soluble wax present in this sample. The gas chromatographic work showed the presence of n-alkenes in the region of C_{70} to C_{80} in all the samples tested. This indicated that there is probability of how wax deposits building even in hot part of the system[7].

The Nile blend gas chromatographic analyses showed that there was a little change in the carbon number distribution. These analyses suggest that there is a very slight tendency for every small quantity of high molecular weight paraffin and asphaltenes to drop out of solution and ellipsoid on pipeline walls[9].

According to Nenniger studied in (1997) the effect of API gravity (light end loss) on yield strength, and the apparent viscosity of Nile blend. It found that yield strength and viscosity are very slightly increased by the light end loss. The small effect of API gravity is consistent with a fluid whose rheology is dominated by wax solids. The waxy solids dominate the rheology properties of the crude, and API gravity of minor significance. Thus preventing light end loss
is not sufficient to avoid rheological problems. He hoped originally to obtain data over a wider range of API gravities.

2.1.14 Paraffin Control

2.1.14.1 Paraffin deposition
Typical paraffin deposits are a mixture of linear and branched chain hydrocarbons (C_{18}) to (C_{70}) combined with a wide variety of organic and inorganic materials that add bulk to the deposit. These deposits vary in consistency from a mushy liquid to a firm hard solid, depending primarily on the amount of oil present. Paraffin deposition takes place by three mechanisms that transport both dissolved and precipitated wax crystal laterally. As the oil cools, a temperature gradient is established that leads to the transport and deposition of wax on the colder pipe wall by molecular diffusion. Particle of previously precipitated wax crystals carried in the oil are transported laterally by Brownian diffusion and shear dispersion[10].

2.1.14.2 Paraffin removal
Most mechanical and thermal treatment for paraffin control is designed for periodic removal. Paraffin is allowed to accumulate for a period of time or until problems arise and then remedial action is taken. These control costs are normally considered to be the standard costs against which chemicals must compete. Usually, these costs are hourly charges for cutting, pig launching, or hot oil or water[10].

2.1.15 Field Application of chemical flow improvers in pipeline.

2.1.15.1 Chemical application
Due to the crudes high pour point and the related high viscosity at low temperatures, intensive laboratory investigations had to be carried out before production startup to find an effective method for flow improvement in winter conditions. From technical and economic aspects, it was decided to use chemical flow improvers for transportation. Field application of the selected flow improver fully confirmed the encouraging lab results; the measured pressure drop across the pipeline under laminar as well as turbulent flow conditions very closely coincided with the values derived from calculations based on lab viscosity and yield stress measurements[11].
2.1.15.2 Comparison of Methods for the Flow Improvement of Paraffinic Crude
In principle there are many different methods for flow improvement of Paraffinic crudes, the most important of which are thermal methods, application of chemicals, and dilution with other hydrocarbons, magnetic and electromagnetic methods, and application of microbes.

2.1.15.3 Dilution with Hydrocarbons
Kumkol oil field produces highly paraffinic crude, a cheap but effective method was applied during Soviet times: paraffin free Siberian crude was transported to the oil field through a double string pipeline. Kumkol crude was diluted in a certain ratio depending on temperature conditions, and the mixture could easily be transported to the refinery. After 1992 Siberian crude was no longer available at the same conditions and alternative methods had to be evaluated[11].

2.1.15.4 Thermal Methods
These methods require excellent pipeline insulations. The latest field applied development maybe is a vacuum insulation of tubing. Furthermore, pipelines have to be electrically heated, or the oil carrying pipelines are bundled with pipelines containing hot water. All these procedure assure trouble free crude transport at any time but at very expensive and mainly used for short pipelines[11].

2.1.15.5 Magnetic and Electromagnetic methods
These methods are occasionally mentioned in literature but up to now they have not been widely applied may be because it is very difficult to explain the exact action mechanism. In principle such treatments aim at a reduction of paraffin precipitation on the pipeline or tank walls by orientation of the paraffin hydrocarbon chains in the magnetic field. One of the most impressing among them is the application of electromagnetic radiation in a 170 miles long crude oil pipeline in Texas where according to information the supplier of the electromagnetic system the amount of paraffin removal during one pigging run was reduced by 95%. Due to limited filed experience with magnetic methods [11].

2.1.15.6 Microbial methods
Microbial methods so far have been mainly applied on well basis but rarely on a field wide basis. In Prudhoe Bay, the application of Microbes for the cracking of long chain alkenes
was recently tested over a period of six months. The application was performed in weeks that due to intensive precipitation of paraffin had to be regularly cleaned with hot oil[11].

2.1.15.7 Chemical methods
Several kinds of products with different action modes are available which are briefly described in the following. The most important group are the so called paraffin crystal modifiers that change the crystallization behavior of paraffins. paraffin crystal modifiers consists of long chain polymers of the ethyl-vinyl-acetate or polyacrylate type, dissolved in different types of hydrocarbons. The cocrystallize with the paraffins and thus paraffin crystals are kept dispersed in the crude and the formation of three dimensional network takes place at lower temperature so that crude viscosity and pour point are lowered substantially. Basically similar chemicals are also sold as “pour point depressant”(PPD), “viscosity modifier” or “paraffin inhibitors”[11].

In Russia further oil field chemicals so called “paraffin depressants” are sold which act in a different way: paraffins, asphaltenes and resins are deliberately precipated from the crude. The remaining liquid crude oil phase becomes much lighter. This procedure achieves the same desired effects such as viscosity and pour point reduction, but leaks to the formation of a crude paraffin slurry in the pipeline where the solid phase will separate as soon as the mixture is not moved, e.g. in storage tanks. Although paraffin depressants are much cheaper than the PPDs, it was decided not to use them because it was not desirable to transport such a two phase system through a long pipeline. A further group products are paraffin dispersers. They mainly consists of surface active agents and fulfill the task of limiting the amount of paraffin sticking to the surface of pipeline and tanks. Some of these products are also able to remove paraffin from equipment surfaces by dispersion; however paraffin dispersers are not routinely used in pipelines and due to the higher application concentration compared to pour point depressant, and the resultant higher cost. Furthermore, the separation of disperser paraffin phase from a wet oil can be problematic because of the formation of stable emulsions[11].

2.1.16 Criteria for the selection of paraffin Inhibitors
A good paraffin inhibitor has to fulfill several tasks, the most important of which are listed below in the order of decreasing significance:
- Viscosity reduction
- Yield stress reduction
- Acceptable cost benefit ratio, i.e. low application concentration combined with low price.
- Long term effectively for several weeks
- Pour point reduction
- Low toxicity
- High flash point

2.1.17 Chemical control techniques for the paraffin deposition

Paraffin deposition generally consists of wax, asphaltene resin and sands etc. the main components is wax. Wax is solid state normal alkanes with (15 – 80) carbon atoms and very few branch chains or even no branch chain. Under the oil formation condition, the wax dissolved in crude oil. But in the course of crude oil following through oil formation into the bottom hole of the well and flowing up to the ground, because of the decrease of pressure, temperature and the outcome of gas, the wax is separated out to from crystals. The wax crystals will grow, aggregate and then precipitate on the wall of oil tube. The process of wax precipitate includes three stages, that is the wax separation, the growing up of wax crystals and the deposition of wax. If the wax crystals are separated from the active points of some solid surface (such as the metal surface, the sand surface) and continuously grow up, there are only two stages for the paraffin deposition. Control of any one of the three stages of wax deposition will reach the goal of paraffin inhibition. Commonly used electric heating cable is example of control wax deposition at the first stage (wax separation) while the glass oil tube and oil coating oil tube are the examples of control wax deposition ate the third stage (wax deposition)[12].

2.1.18 Control Systems:

2.1.18.1 Systems
A system can be defined as a physical or logical device that performs an operation on a signal. Therefore we can say that systems process input signals to produce output signals. System is a set of objects linked by different interactions and relationships. The elements and boundaries
of a system are determined by the interactions and mutual relationships, that are taken into consideration[13].

2.1.18.2 Control Classification
Control is first classified as being either manual or automatic. This division generally refers to the amount of human effort needed to achieve a common function.

A. Manual control

It is voluntarily initiated within the system with very little human effort. The terms open-loop and forward-feed are frequently used to describe manual control systems. Valve adjustments and switching functions are examples of manual control operations. In general, this type of control is achieved by some degree of physical effort on the part of a human operator.

B. Automatic control

by comparison, applies to those things that are achieved, during normal operation, without human intervention. This type of control is used where continuous attention to system operation would be demanded for a long period without interruptions. Automatic control does not, however, necessarily duplicate the type of control achieved by a human operator. Equipment that employs automatic control is limited to only those things that can be forecast by the input data. Terms such as closed-loop control and feedback are commonly used to describe automatic control functions [14].

2.1.18.3 Open-loop Control

Open-loop control is relatively easy to achieve because it does not employ any automatic equipment to compare the actual output with the desired output. In manufacturing, open-loop operations are achieved by adjustment of the system to some predetermined setting by a human operator. The system then responds to this setting without any modification. Any changes made in operation are based entirely on some outside human judgment to correct the desired output[14].

2.1.18.4 Closed-loop Control

Closed-loop refers to a type of system that is self-regulating. In this type of system, the actual output is measured and compared with a predetermined output setting. A feedback signal generated by the output sensing component is used to regulate the control element so that the
output conforms to the desired value. The term feedback refers to the direction in which the measured output signal is returned to the control element. In a sense, the output of this type of system serves as the input signal source for the feedback control element. Closed-loop control is so named because of the return path created by the feedback loop from the output to the input [14].

2.1.19 Analog and Digital Controllers

The job of the controller is to compare the process signal from the transmitter with the set point signal and to send out an appropriate signal to the control valve. Analog controllers use continuous electronic or pneumatic signals. The controllers see transmitter signals continuously, and control valves are changed continuously. Digital computer controllers are discontinuous in operation, looking at a number of loops sequentially. Each individual loop is polled every sampling period. The analog signals from transmitters must be sent through analog-to-digital (A/D) converters to get the information into the computer in a form that it can use. After the computer performs its calculations in some control algorithm, it sends out a signal that must pass through a digital-to-analog (D/A) converter and a “hold” that sends continuous signal to the control valve [14].
Fig.(2.1): Digital control system.
2.2 Pipeline Leak Detection Systems

Methods used to detect product leaks along a pipeline can be divided into two categories, externally based (direct) or internally based (inferential).

2.2.1 Externally based methods detect leaking product outside the pipeline and include traditional procedures such as right-of-way inspection by line patrols, as well as technologies like hydrocarbon sensing via fiber optic or dielectric cables.

2.2.2 Internally based methods, also known as computational pipeline monitoring (CPM), use instruments to monitor internal pipeline parameters (i.e., pressure, flow, temperature, etc.), which are inputs for inferring a product release by manual or electronic computation [16].

The method of leak detection selected for a pipeline is dependent on a variety of factors including pipeline characteristics, product characteristics, instrumentation and communications capabilities, and economics [17]. Pipeline systems vary widely in their physical characteristics and operational functions, and no one external or internal method is universally applicable or possesses all the features and functionality required for perfect leak detection performance. However, the chosen system should include as many of the following desirable leak detection utilities as possible [16].

- Accounts for heat transfer
- Provides the pipeline system’s real time pressure profile
- Possesses accurate product release alarming and high sensitivity to product release
- Allows for timely detection of product release
- Offers efficient field and control center support
- Requires minimum software configuration, tuning and minimum impact from communication outages
- Accommodates complex operating conditions
- Is available during transients
- Is configurable to a complex pipeline network
- Performs accurate imbalance calculations on flow meters
- Possesses dynamic alarm thresholds
- Possesses dynamic line pack constant
Accommodates product blending
- Accommodates slack-line and multiphase flow conditions
- Accommodates all types of liquids
- Identifies leak location
- Identifies leak rate
- Accommodates product measurement and inventory compensation for various corrections (i.e., temperature, pressure, and density); and

2.3 Major components of a computer-based LDS
The utilization of computer systems in pipeline monitoring allows the greatest amount of data to be collected, analyzed, and acted upon in the shortest amount of time. For these reasons, most pipeline systems today employ some form of computer-based monitoring using commercially available or custom-designed software packages to run the system [18]. Leak detection is just one of many functions that can be performed with computer-based systems, which generally consist of two major elements: instrumentation and a supervisory computer with associated software and communications links.

2.3.1 Instrumentation
Instrumentation includes the flow meters, pressure transducers, sensors, and cables situated along the pipeline (externally or internally) which measure parameters such as line pressure, temperature, flow, product characteristics, and the presence of hydrocarbons. Because the effectiveness of any pipeline LDS is limited primarily by the sensitivity and accuracy of the installed instrumentation, it is critical to select the best performing setup for a given operating scenario. Instrument specifications should be prudently compared to a pipeline’s operating design to make the best use of the manufacturer’s declared accuracy and linearity [16]. Additionally, all practical means should be taken to reduce sources of instrument noise, which can inhibit the performance of an LDS. Mechanical resonance and electrical interference are primary sources of instrument noise. Mechanical resonance must be considered during the design of process piping and placement of the instrument package. Proper instrument grounding and the use of shielded signal cables will serve to reduce electrical noise. If these measures of noise reduction are not successful, signal conditioning (bandwidth adjustment, digital filters, or data smoothing programs) may be required. Another means of reducing the
The impact of mechanical noise on pipeline systems is the use of inline surge or divert tank provides some general guidelines to follow when selecting field instrumentation[19]:

- Choose instrumentation based on performance and not economic grounds. It is better to install fewer high quality pieces equipment than numerous poor ones.
- Equipment compatibility is important. Use transducers, interface modules, and other hardware that use standard communications protocol.
- Where possible, install instruments that are self-checking or self-diagnosing, or install dual systems.
- Seek independent references, user experience, or validation of the instruments chosen. Most equipment performs differently in real applications than under the published ideal conditions.

2.4 SCADA Communications
The Supervisory Control and Data Acquisition (SCADA) system is a computer-based communications system that monitors, processes, transmits, and displays pipeline data for the controller [16]. SCADA systems may be used directly for leak detection, they may provide support for an LDS, or an LDS may operate independently of SCADA. Generally, a pipeline LDS will use the data generated by a SCADA system to aid in assessing the potential for a product release. SCADA systems collect real-time data from field instruments using Remote Terminal Units (RTUs).

[Photograph](image)

Photograph. (2.3): SCADAPack(RTU)[16].
Programmable Logic Controllers (PLCs), and other electronic measurement devices, which are placed at intervals along the pipeline. Communication with these devices can occur in many ways, including microwave, cellular, satellite, leased line, etc., but the most common media are dedicated phone circuits and terrestrial- and satellite-based radio systems [16]. An emerging trend is to use multiple methods of communicating based on the concept that each method will have a cost or performance advantage for a given installation [16].

Data from RTUs or PLCs are gathered into a Master Terminal Unit (MTU) which consists of one or more central computers built around a real-time, memory-resident database. The MTU displays the current operating conditions for the controller, who, in turn, can act on these data if necessary. Messaging between the field devices and the MTU is known as the communications protocol [16]. The protocol is considered “polled” when the MTU requests data from each device consecutively. When the last device is scanned, the MTU will automatically request information from the first one, creating a ceaseless polling cycle. The SCADA system polling rate, the time between successive communications between the RTU and MTU, has steadily improved over the years and has been reduced to less than 0.25 seconds in high priority areas on some pipelines [21]. SCADA communications may also be non-polled. For example, RTUs may report without being polled on a time-scheduled basis or when field conditions change. LDSs that rely on the SCADA system to receive operating data are directly affected by the polling rate. Longer polling cycles typically translate to degraded leak detection sensitivity. Most modern SCADA systems include quality checking software to assess the validity of the data before any calculations are computed and displayed [19]. Research suggests that this type of continuous quality control greatly improves the sensitivity of the system. In addition, advanced SCADA systems can include predictive modeling to assess “what if” operating scenarios, handle automatic startup and shutdown routines, and evaluate operating strategies for cost-benefit optimization[19]. For additional discussion of SCADA system design factors and their effects on the quality and timeliness of the data required by an LDS, see API Document 1130, Computation Pipeline Monitoring [16].
2.4.1 SCADA benefits:
SCADA offers unique benefits:

- Reliability
- Quick response via real time.
- Economical operating
- Alarming.
- Less man errors
- System scalability.
- High performance presentation.
- High safety factor.

2.4.2 SCADA system consists of:
1. One or more field data interface devices, usually RTUs, or PLCs which interface to field sensing devices and local switchboxes and valve actuators

Photograph.(2.4):SCADA RTU[16]..
2. A communication system used to transfer data between field data interface devices and control units and the computers in the central host. The system can be radio, telephone, cable, satellite, etc., or any combination of these.

3. A central host computer server(sometimes called SCADA center, master station or master terminal unit (MTU).

4. A collection of standard and/or custom software, sometimes called Human Machine Interface (HMI) software or man machine interface (MMI) software systems used to provide the SCADA central host and operator terminal application, support the communications system, and monitor and control located field data interface devices.

2.4.3 Field data interface devices

Field data interface devices form the eyes and ears of SCADA system. Devices such as reservoir level meters, water flow meters, valve position transmitters, temperature transmitters and pressure meters all provide information that can tell an experienced operator how well a petroleum pass through the pipeline.

The information that is passed to and from the field data interface devices must be converted to a form that is compatible with language of the SCADA system to achieve this, some form of electronic field data interface is required. RTUs are primarily used to convert electronic signals received from field interface devices into language (known as the communication protocol) used to transmit the data over a communication channel.

2.4.4 Remote terminal unit (RTU):

SCADA RTU is a small computer which provides intelligence in the field, and allows the central SCADA master to communicate with the field instruments. It is a standalone data acquisition and control unit, its function is to control process equipment at the remote site, acquire data from the equipment, and transfer the data back to central SCADA system.

2.4.5 Central Host Computer

The central host computer or master station is most often a single computer or network of computer servers that provide a man machine operator interface to the SCADA system. The computers process the information received from and sent to RTU sites and present it to
human operators in a form that the operators can work with. Operator terminals are connected to the central host computer by a LAN/WAN so that the viewing screens and associated data can be display for the operators. Recent SCADA systems are able to offer high resolution computer graphics to display a graphical user interface or mimic screen of site.

2.4.6 HMI/MMI(Human Machine Interface/Man Machine Interface):

HMI provide the following:

- Apparatus which present process data to a human operators and through it, the operator can control the process so it can be interfaced between the operator and remote system.
- Presentation on multicolor VDUs in order to provide important information.
- Mimic board diagram for overview presentation with audible alarm facility.

2.5 Internal Leak Detection Systems

Computational pipeline monitoring (CPM). CPM refers to algorithmic monitoring tools that are used to enhance the abilities of a pipeline controller to recognize anomalies which may be indicative of a product release [16]. CPM operates by providing an alarm and displaying other related data to the controller who, in turn, would investigate the reason for the alarm and initiate a response if the anomaly represents a product release. CPM does not include externally based LDSs which operate on the non-algorithmic principle of physical detection of a product leak [16]. CPM mainly relies on the data collected from the field instruments, which are continuously input into a computer program that mathematically or statistically analyzes the information. Analysis results are produced in the form of parameter estimates, which in turn are subjected to some probability law or decision criteria to determine if a leak is present [16].

2.6 External Leak Detection Systems

2.6.1 Acoustic Emissions

Leak detection in pipelines using acoustic emissions technology is based on the principle that escaping liquid creates an acoustic signal as it passes through a perforation in the pipe. Acoustic sensors affixed to the outside of the pipe monitor internal pipeline noise levels and locations. These data are used to create a baseline “acoustic map” of the line. When a leak
occurs, the resulting low frequency acoustic signal is detected and analyzed by system processors. Deviations from the baseline acoustic profile would signal an alarm. The received signal is stronger near the leak site thus enabling leak location.

2.6.2 Fiber Optic Sensing

With this technology, fiber optic sensing probes are driven into the soil beneath or adjacent to the pipeline. In the presence of hydrocarbons, the patented covering of the sensor changes its refractive index. This change is registered optically by the sensor and converted to a parts-per-million reading of hydrocarbons.

2.6.3 Digital controller

The design computer become involved in process control in the 1960s. The first instance in which closed loop control was implemented by a digital computer in an industrial plant was done by Texaco’s Port Arthur plant on March 15th, 1959. By 1960 many control instrument companies responded to this new technology and offered computer-based systems. "Analog controllers should gradually evolve into digital devices, providing accuracy at low cost. These controllers will be relatively simple to combine into multipoint configurations, which can be applied to optimize unit process on local basis[26]. More discoveries concerning digitizing PID controller were made, and arguments for implementing controllers on microprocessors were brought up as microprocessors could handle calculations directly in engineering units[26].

Due to advances of technology, the PID controller is widely and commonly used.

Digital PID controllers is commonly used because it is more suitable to design for a complex system for the purpose of reducing cost, and is more immune to noise than an analog PID.
Chapter Three
Material and Method

3.1 Introduction
This chapter contains information about types of materials used in this research such as: sensors or transmitters, controllers, valves, type of control, and brief history about MATLAB software. Also the methods for determining the overall transfer function of the system and the stability tests, tuning controllers and overall system response.

3.2 Sensors and measuring devices
The successful operation of any feedback control system depends in a very critical manner. There are different commercial measuring devices which differ either in the basic measuring principle or their construction characteristics[23].

A sensor is a device that measures and converts a physical quantity into a signal which can be observed and recorded by property instrument [24]. There are many types of measuring devices used to measure various conditions including :temperature, pressure ,level, humidity , speed, motion, distance and light detection[24].

Table (3.1) :list typical measuring devices encountered in various applications of process control[25].

<table>
<thead>
<tr>
<th>Measuring process variable</th>
<th>Measuring device</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>temperature</td>
<td>Thermocouple</td>
<td>Most common for relatively low temperature</td>
</tr>
</tbody>
</table>
Infrared analyzers  
Ultraviolet analyzers  
Visible –radiation analyzers  
Turbidimetry analyzers  
Potentiometry  
Conductimetry  
Osillometric  
PH meters  
Long times required for analysis.  
Convenient for one or two chemicals.  
Not very Convenient for process control

The measuring device needed in this work is temperature thermocouple, they are used to detect the temperature.

### 3.2.1 Type of controllers

Process control is the measurement of a process variable, the comparison of that variables with its respective set point, and the manipulation of the process in a way that will hold the variable at its set point when the set point changes or when a disturbance changes the process[26].

One way to improve the step response of a control system is to add a controller to the feedback control system, the closed loop systems can be controlled by Proportional control, Proportional Integral (PI) control and Proportional plus Integral plus Derivative (PID) control.

The PID control algorithm is made of three basic responses, Proportional (or gain), integral (or reset), and derivative[26].

Derivative is the third and final element of PID control. Derivative responds to the rate of change of the process (or error). Derivative is the normally applied to the process only.

Analog PID controllers are common in many applications. They can be easily constructed using analog devices such as operational amplifiers, capacitors and resistors. They are reliable in mechanical feedback systems and able to satisfy many control problems.
### 3.2.2 Analog VS Digital

Definitions:

- **ANALOG**
  
  quantities or representations that are variable over a continuous range. Analog variables can take an infinite number of values, while digital variables are limited to defined states. Analog systems are more accurate in reproducing a quantity, variable, or signal. Digital signals are more resistant to noise and can be transmitted with greater efficiency.

  Analog instrumentation is usually hardwired and is dedicated to continuously performing a particular control function.

- **DIGITAL**
  
  A term used to define a quantity at discrete levels rather than over a continuously variable range. This distinction has little practical relevance, as the resolution is limited only by the range of power of the used. The greater the number the smaller the analog quantity required to cause a digital change.

  Digital instrumentation is often shared and performs its control function in a sequential manner.

### 3.2.3 Selecting of the Controller Transfer Function

In this work P, PI and PID will selected and install in the control loop, each at the time. The controller will be tuned, the stability will be analyzed and the process will be simulated.

### 3.2.4 Modeling of the system

The first step in the control design process is to develop appropriate mathematical models of the system derived either from physical laws or experimental data.

### 3.2.5 Dynamic of the system

Is system that change or evolve in time according to fixed rule.
3.2.6 Transfer Function representation

System has extremely important property that if the input to the system is sinusoidal, then the output will also be sinusoidal at the same frequency but in general with different magnitude and phase. These magnitude and phase differences as a function of frequency are known as frequency response of the system. The Laplace transform is used to convert a system's time domain output/input representation, which known as transfer function. The chart describes the overall methodology.

![Flow diagram of research methodology](image)

3.2.7 System stability and tuning

Mathematical models of a system have been obtained in transfer function form, and then these models can be analyzed to predict how the system will respond in both the time and frequency domains.
3.2.8 Stability

Systems have several properties—such as controllability, observability, stability, and invertibility—that play a very decisive role in their behavior. From these characteristics, stability plays the most important role. The most basic practical control problem is the design of a closed-loop system such that its output follows its input as closely as possible, unstable systems cannot guarantee such behavior and therefore are not useful in practice. Another serious disadvantage of unstable systems is that the amplitude of at least one of their state and/or output variables tends to infinity as time increases, even though the input of the system is bounded. This usually results in driving the system to saturation and in certain cases the consequences may be even more undesirable: the system may suffer serious damage, such as burn out, break down, explosion, etc. For these and other reasons, in designing an automatic control system, our primary goal is to guarantee stability. As soon as stability is guaranteed, then one seeks to satisfy other design requirements, such as speed of response, settling time, bandwidth, and steady-state error. The concept of stability has been studied in depth, and various criteria for testing the stability of a system have been proposed. Among the most celebrated stability criteria are those of Routh, Hurwitz, Nyquist, Bode [29].

Mathematically, the stability of a linear system can be determined by an analysis of the roots of the characteristic equation from the differential equation describing the process(which corresponds to the roots of the denominator of the transfer function). Here the roots of the characteristic equation for given K are on the imaginary axis, and the system is oscillating[30].

3.2.9 Stability test

If all poles of the transfer function (values of at which the denominator equals zero ) have negative real parts, then the system is stable. If any pole has a positive real part , then the system is unstable. On the complex s-plane, all poles must be in the left half plane(LHP) to ensure the stability. If any pair of poles is on the imaginary axis , then the system is marginally stable and the system will oscillate.
To ensure a good performance of the system, each of the control loops mentioned earlier should be analyzed for the stability, separately. For the present work, four methods have been used to check the stability of the system. Such methods are:

- Routh Hurwitz
- Root Locus plot
- Bode plot

### 3.2.10 Routh’s Criterion

One absolute method of determining whether complex or real roots lie in the right hand plane is by use of Routh’s criterion the method entails systematically generating a column of numbers that are then analyzed for sign variations. The first step is to arrange the denominator of the transfer function into descending powers of s. All terms including those that are zero should be included\[^{30}\].

### 3.2.11 Direct Substitution Analysis

The closed-loop poles may lie on the imaginary axis at the moment a system becomes unstable. We can substitute $s = j\omega$ in the closed-loop characteristic equation to find the proportional gain that corresponds to this stability limit (which may be called marginal unstable). The value of this specific proportional gain is called the critical or ultimate gain. The corresponding frequency is called the crossover or ultimate frequency\[^{31}\]. The ultimate gain and ultimate period that can be used in Z-N continuous cycling relations, and the result on ultimate gain is consistent with Routh array analysis and limited to relatively simple systems.

### 3.2.12 Root locus analysis

It is one of the most powerful techniques in controller design and analysis when there is no time delay. Root locus is a graphical representation of the roots of the closed-loop characteristic polynomial (i.e., the closed-loop poles) as a chosen parameter is varied. Only the roots are plotted. The analysis most commonly uses the proportional gain as the parameter.
A Root Locus plot is a figure that shows how the roots of the closed loop characteristic equation vary as the gain of the feedback controller changes from zero to infinity. The abscissa is the real part of the closed loop root; the ordinate is the imaginary part. Since we are plotting closed loop roots, the time constants and damping coefficients that we pick off these root locus plots are all closed loop time constants and closed loop damping coefficients [15].

- Root locus are the plots, in complex plane, of the roots of the OLTФ.
- They are very useful to determine the stability of closed loop system as the gain $K_c$ changes.

The value of the frequency $\omega_{co}$ which take from the Root locus plot used to calculate the limit gain and ultimate period ($K_c$ and $P_u$)

$$P_u = \frac{2\pi}{\omega_{co}}$$

Fig.(3.2): Root Locus

System: sys
Gain: 321
Pole: 0.866 + 13.9i
Damping: -0.0623
Overshoot (%): 122
Frequency (rad/sec): 13.9
### 3.2.13 Bode Plots

Bode plots require two curves to be plotted instead of one. This increase in the number of plots is well worth the trouble because complex transfer functions can be handled much more easily using Bode plots. The two curves show how magnitude ratio and phase angle (argument) vary with frequency[31].

![Bode Diagram](image)

Fig.(3.3): Bode plot

To find the Amplitude Ratio (AR)

\[
AR = \frac{K_1 K_2 \ldots K_n}{\sqrt{1+(\omega \tau_1)^2} \sqrt{1+(\omega \tau_2)^2} \sqrt{1+(\omega \tau_3)^2}}
\] ................................................................. 3.2

The value of the frequency \(\omega_{co}\) which take from the Bode plot used to calculate the limit gain and ultimate period \((K_c \text{ and } P_u)\)

\[
P_u = \frac{2\pi}{\omega_{co}}
\] ................................................................. 3.3

### 3.2.14 Tuning controllers

Tuning means setting the adjustable parameters (proportional band/gain, integral gain/reset, derivative gain/rate) of a controller to give best performance. For the PID controller.
3.2.15 Ziegler – Nichols Tuning Technique:

The Ziegler-Nichols (ZN) controller settings (J. G. Ziegler and N. B. Nichols, Trans. ASME 64: 759, 1942) are pseudo-standards in the control field. They are easy to find and to use and give reasonable performance on some loops. The ZN method consists of first finding the ultimate gain $K_c$ the value of gain at which the loop is at the limit of stability with a proportional-only feedback controller. The period of the resulting oscillation is called the ultimate period, $P_u$ (minutes per cycle). The ZN settings are then calculated from $K_u$ and $P_u$ by the formulas given in Table for the three types of controllers. Notice that a lower gain is used when integration is included in the controller (PI) and that the addition of derivative permits a higher gain and faster reset[15].

The Z-N method is based on frequency response analysis. Unlike the process reaction curve method which uses data from the open-loop response of system. The Z-N tuning technique is a closed –loop procedure.

1- Bring the system to the desired operation level (design conditions).
2- Using P- control only , and with the feedback- loop closed , introduce a sinusoidal set pt. changing with low amplitude and varying frequency until the system oscillates continuously , the frequency of continuous oscillation is the crossover frequency $\omega_{co}$ .let M = amplitude ratio of the system's response at the crossover frequency Ultimate period $P_u = \frac{2\pi}{\omega_{co}}$.
3- Z.N recommended the following setting for feedback controller:

Table (3.2): Ziegler-Nichols adjustable parameters

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>$K_c$</th>
<th>$\tau_i$(min)</th>
<th>$\tau_D$(min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>$0.5K_u$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PI</td>
<td>$0.45K_u$</td>
<td>$P_u/1.2$</td>
<td></td>
</tr>
<tr>
<td>PID</td>
<td>$0.6K_u$</td>
<td>$P_u/2$</td>
<td>$P_u/8$</td>
</tr>
</tbody>
</table>
3.2.16 Time Response
The time response represents how the state of dynamic system changes in time when subjected to particular input. Since the models has been derived consist of differential equations, some integration must be performed in order to determine the time response of the system. Fortunately, MATLAB provides many useful resources for calculating time responses for many types of inputs.

3.2.17 MATLAB Software
MATLAB is integrated technical computing environment that combines numeric computation, advanced graphical and visualization, and high-level programming language. The MATLAB software was originally developed to matrix laboratory. Its capabilities have expanded greatly in recent years and today it is a leading tool for engineering concepts in mathematics. Being able to plot mathematical functions and data, MATLAB, can be used in research development and industry. It is used in this research for tuning through different tuning techniques.

3.2.18 Digital Control Design for Proportional Integral Derivative (PID) control
Several methods can be used to design a digital PID. One of the methods is to design analog PID first, then convert the s-domain into the z-domain with appropriate approximation. A digital PID can also be directly designed by the root locus and response methods.

The conversion from s-domain into z-domain is quick and easy. The conversion can be done by using difference approximation, ZOH (zero-order hold), bilinear transformation or first order hold. In this section, the difference approximation equation is derived.
Chapter Four

Result and Discussion

4.1.1 Introduction
In this chapter the results of control system have been discussed and tested for stability, tuning and response.

4.1.2 Control Strategy:
The crude is transported from the Heglig fields in the south west of Sudan inside a 1610 km, 71 cm(28 in) pipeline to the Marine Terminal in the Red Sea via 6 pump-stations, two control loops were proposed and implemented.

4.1.3 Control loops configuration:
1. Heat exchanger
2. Temperature controller.
3. Composition controller.
4. Therminol control valve
5. Additives control valve
6. SCADA system.
Fig.(4.1) : Physical diagram for Temperature and viscosity control loop

4.1.4 The controller transfer function ($G_c$)

P, PI and PID will be selected and installed in the control loop. The controller will be tuned, the stability will be analyzed and the process will be simulated.
4.1.5 Identification of transfer functions

4.1.6 Transfer function of the valve

![Diagram of pneumatic valve](image)

Fig.(4.2): pneumatic valve

The position of the stem or equivalently the plug at the end of the stem will determine the size of the flow rate. The position of the stem is determined by the balance of forcing acting on it, there are:

\[ PA - Kx - C \frac{dx}{dt} = M \frac{d^2x}{dt^2} \] ..........................\text{4.1}

\[ PA = \text{force exerted by the compressed air at the top of the diaphragm}. \]

\[ KX = \text{force exerted by the spring, Hooke's law}. \]

\[ C \frac{dx}{dt} = \text{fractional forces exerted upward and resulting from close contact of the stem with the valve packing}. \]

\[ \frac{M}{K} \frac{d^2x}{dt^2} + x + \frac{C}{K} \frac{dx}{dt} = \frac{A}{K} P \] ..........................\text{4.2}

\[ \text{let } \frac{M}{K} = \tau^2, \frac{C}{K} = 2\xi \tau, \frac{A}{K} = KP \] ..........................\text{4.3}

59
\[ \tau^2 \frac{d^2 x}{dt^2} + 2 \xi \tau \frac{dx}{dt} + x = K_p P \] ........................................... 4.4

Taking Laplace TF for equation (4.4)

\[ \tau^2 s^2 X(s) + 2 \xi \tau X(s) + X(S) = K_p P(s) \]

\[ X(s)[\tau^2 s^2 + 2 \xi \tau s + 1] = K_p(s) \]

The T.F is:

\[ G(s) = \frac{X(s)}{P(s)} = \frac{K_p}{\tau^2 s^2 + 2 \xi \tau s + 1} \] ........................................... 4.5

The valve can be represented by second order T.F, say:

\[ G_v = \frac{1}{(0.4s+1)(0.01s+1)} \] ........................................... 4.6

4.1.7 Dynamics of the thermocouple for temp measurement:

\[ hA \theta - hA y = mcp \frac{dy}{dt} \] ........................................... 4.7

\( Y=\text{temp to be read by the thermocouple.} \)

\( \theta = \text{the surrounding temp.} \)

\( h=\text{heat transfer coefficient.} \)

\( A=\text{heat transfer area.} \)

\( m=\text{mass of the joint of thermocouple.} \)

\( cp=\text{specific heat.} \)

Dividing by \( hA \):

\[ \frac{mcp}{hA} \frac{dy}{dt} + y = \theta \]

\[ \tau \frac{dy}{dt} + y = \theta \]

Taking L.T:
\[ \tau s Y(s) + Y(s) = \theta(s), Y(s)(\tau s + 1) = \theta(s) \]

The sensor T.F is:

The sensor is too fast and time constant is small but it has a dead time of transfer function \( e^{-Ds} \) very short and can be neglected

\[ Y(s) = \frac{1}{\tau s + 1} \theta(s) \]  

The thermocouple can be represented by a first order:

\[ G_m = \frac{1}{0.01s + 1} \]

4.1.7.1.1 **Transfer function of the heat exchanger**

Applying the low of conservation of energy:

\[ M_1 c_p \frac{d\theta_1}{dt} = \dot{m} c_p \theta_0 + Q - \dot{m} c_p \theta_1 \]

\[ M_1 = \rho v \text{ hold up mass} \]

\[ M_1 c_p \frac{d\theta_1}{dt} + \dot{m} c_p \theta_1 = \dot{m} c_p \theta_0 + Q \]

Dividing eq(11)by \( \dot{m} c_p \)

\[ \frac{M_1 c_p}{\dot{m} c_p} \frac{d\theta_1}{dt} + \theta_1 = \theta_0 + \frac{1}{\dot{m} c_p} Q \]

Let

\[ \frac{M_1}{\dot{m}} = \tau \text{ time constant=Residence time} \]

\[ \tau \frac{d\theta_1}{dt} + \theta_1 = \theta_0 + \frac{1}{\dot{m} c_p} Q \]

Taking L.T of eq(12)

\[ \tau s \theta_1(s) + \theta_1(s) = \theta_0(s) + \frac{1}{\dot{m} c_p} Q(s) \]
\[ \theta_1(\tau s + 1) = \theta_0(s) + \frac{1}{mcp} Q(s) \]

\[ \therefore \theta_1 = \frac{1}{(\tau s + 1)} \theta_0(s) + \frac{1}{(\tau s + 1) mcp} \tag{4.13} \]

\[ \dot{m} = 1100 \text{m}^3/\text{hr} \]

\[ c_p = 2.27 \]

\[ D = 28 \text{ in} \]

\[ r = 28 \times 2.54 \times 10^{-2} = 0.7112 \text{m} \]

\[ V = \frac{\pi D^2}{4} \cdot h = 0.397 \times 3 \text{m}^3 = 1.191 \text{ m}^3 \]

\[ V = 1.191 \text{ m}^3 \]

\[ \rho = 850.4 \frac{kg}{m^3} \]

\[ \tau = \frac{\dot{V}}{V} = \frac{1.191}{1100} = 0.0011 \text{ hr} = 3.9 \text{ sec} \]

\[ \text{load variable} = \frac{Q(s)}{\dot{m}c_p} = 0 \]

\[ G_p = \frac{\theta_1(s)}{\theta_0(s)} = \frac{1}{(\tau s + 1)} = \frac{1}{(3.9s + 1)} \]

4.1.7.1.2 Transfer function of the composition:

\[ F_0C_{A_0} = \text{flow of A into the system.} \]

\[ FC_A = \text{flow of A out of the system.} \]

\[ \frac{d}{dt} (vC_A) = \text{the rate of change of A inside the tank.} \]

\[ \therefore F_0C_{A_0} - FC_A = \frac{d}{dt} (vC_A) \tag{4.14} \]

\[ F_0C_{A_0} = \frac{d}{dt} (vC_A) + FC_A \tag{4.15} \]
Dividing eq (15) by $F$

$$\frac{F_0}{F} C_{A_0} = \frac{d}{dt} \left( \frac{\nu C_A}{F} \right) + C_A$$

$$\tau = \frac{\nu}{F}$$

$$K = \frac{F_0}{F}$$

$$KC_{A_0} = \tau \frac{d}{dt} (C_A) + C_A \text{ .................................................................} 4.16$$

Taking LT for eq (16)

$$KC_{A_0}(s) = \tau \frac{d}{ds} (C_A)(s) + C_A(s)$$

$$KC_{A_0}(s) = C_A(s)(\tau s + 1)$$

$$\frac{C_A(s)}{C_{A_0}(s)} = \frac{K}{(\tau s + 1)}$$

$$G_c = \frac{K}{(\tau s + 1)}$$

The composition can be represented by a first order say:

$$G_c = \frac{1}{(3.9 s + 1)}$$

### 4.1.8 Controller stability

A proportional controller increases the speed of the dynamic response of a process, but does not change the order of the process for 1st order and 2nd order.

The output of a proportional controller equals $K_c$ multiplied by the error. A proportional controller is best used to prevent deviations beyond a certain limit, if it is not necessary to maintain a small range at particular set point. There is some offset associated with proportional control, which is why it is not used for operating within a small range. Typical applications of p-only controllers are for level and pressure controllers.
control loops:

loop 1:

Proportional Controller (P):

\[ G_c = K_c \]

Process T.F \( G_p = \frac{1}{(3.9 s + 1)} \)

Valve T.F, \( G_v = \frac{1}{(0.4 s + 1)(0.01 s + 1)} \)

Sensor T.F, \( G_m = \frac{1}{(0.01 s + 1)} \)

loop 2:

Proportional Controller (P):

\[ G_c = K_c \]

Composition T.F, \( G_p = \frac{1}{(3.9 s + 1)} \)

Valve T.F, \( G_v = \frac{1}{(0.4 s + 1)(0.01 s + 1)} \)

Sensor T.F, \( G_m = \frac{1}{(0.02 s + 1)} \)

Block diagram for loop 1:
4.2 Analysis and optimum settings for Loop1 (heat exchanger).

4.2.1 Routh Hurwitz Method:
The overall TF:

\[
G(s) = \frac{\pi f}{1 + \pi l}
\]

\[
\pi f = \frac{K_c}{(0.4s + 1)(0.01s + 1)(3.9s + 1)}
\]

\[
\pi l = \frac{K_c}{(0.4s + 1)(0.01s + 1)(0.01s + 1)(3.9s + 1)}
\]

\[
1 + \pi l = \frac{(0.4s + 1)(0.01s + 1)(0.01s + 1)(3.9s + 1) + K_c}{(0.4s + 1)(0.01s + 1)(0.01s + 1)(3.9s + 1)}
\]

\[
G(s) = \frac{K_c(0.01s + 1)}{(0.4s + 1)(0.01s + 1)(0.01s + 1)(3.9s + 1) + 2K_c}
\]

The characteristic equation is:

\[
(0.4s + 1)(0.5s + 1)(0.2s + 1)(3.9s + 1) + K_c = 0
\]

\[
0.0002s^4 + 0.03124s^3 + 1.61091s^2 + 4.311s + (1 + K_c)
\]

Number of rows = n+1 = 4+1 = 5
For the system to be critically stable the row number $n$ is equal to zero:

\[
6.8255 - 0.0312(1 + K_c) = 0 \tag{4.21}
\]

\[
6.8255 - 0.0312 - 0.0312 K_c = 0 \tag{4.22}
\]

\[
K_c = \frac{6.7943}{0.0312} = 226.6 \tag{4.23}
\]

The ultimate gain, $K_u$=226.6

**4.2.2 Direct substitution method:**

To find the crossover frequency, $\omega_{co}$

Set $s = i\omega$

\[
0.0002s^4 + 0.03124s^3 + 1.61091s^2 + 4.311s + (1 + K_c)
\]

\[
0.15\omega^4 - 1.522i\omega^3 - 4.67\omega^2 + 4.67i\omega + (1 + K_c) \tag{4.24}
\]

\[
Re = 0.0002\omega^4 - 1.61091\omega^2 + (1 + K_c) \tag{4.25}
\]

Taking the imaginary part

\[
im = 4.311\omega - 0.03124\omega^3 \tag{4.26}
\]

\[
im = \omega(4.311 - 0.03124\omega^2)
\]

\[
4.311 - 0.03124\omega^2 = 0
\]

\[
4.311 = 0.03124\omega^2
\]

\[
\omega_{co} = 11.74 \frac{rad}{sec}
\]

Taking the real part
\[ 0.0002\omega^4 - 1.61091\omega^2 + (1 + K_c) = 0 \]

\[ 0.0002(11.74)^4 - 1.61091(11.74)^3 + (1 + K_c) = 0 \]

\[-K_c = -218.241\]

\[ K_c = 218.241 \]

\[ Pu = \frac{2\pi}{\omega_{co}} = \frac{2\pi}{11.74} = 0.535 \text{sec} \]

### 4.2.3 Determination of adjustable parameters, these are determined using Z-N.

Table (4.1): Ziegler-Nichols adjustable controller parameters for heat exchanger control loop for Routh-Hurwitz

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Kc</th>
<th>( \tau_i ) (min)</th>
<th>( \tau_D ) (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>0.5Ku</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>0.45Ku</td>
<td>( \frac{pu}{1.2} )</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>0.6Ku</td>
<td>( \frac{pu}{2} )</td>
<td>( \frac{pu}{8} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Kc</th>
<th>( \tau_i ) (min)</th>
<th>( \tau_D ) (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>109.12</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>98.21</td>
<td>2.33</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>130.9</td>
<td>1.4</td>
<td>0.35</td>
</tr>
</tbody>
</table>

\( K_c = 109.12 \) for P-action:

\[ 0.0002s^4 + 0.03124s^3 + 1.61091s^2 + 4.311s + (1 + K_c) \] ……………………….. 4.27

Checking Stability using Routh:

\[
\begin{bmatrix}
0.0002 & 1.61091 & 110.12 \\
0.03124 & 4.311 & 0 \\
1.543 & 110.12 & 0 \\
2.139 & 0 & 0 \\
110.12 & 0 & 0 \\
\end{bmatrix}
\]
Data of the first column in Routh array:

\[
\begin{bmatrix}
0.0002 \\
0.03124 \\
1.543 \\
2.139 \\
110.12
\end{bmatrix}
\]

The system is stable, all elements of the first column were positive and there is no change of sign.

**4.2.4 Offset investigation:**

\[G(s) = \frac{\ddot{y}(s)}{\ddot{y}sp(s)} = \frac{\pi f}{1+\pi t} \] ................................................................. 4.28

\[
\frac{\ddot{y}(s)}{\ddot{y}sp(s)} = \frac{Kc(0.01s+1)}{0.0002s^4+0.03124s^3+1.61091s^2+4.311s+110.12}
\] ................................................................. 4.29

\[Kc = 109.12 \text{ from tuning} \]

\[
\frac{\ddot{y}(s)}{\ddot{y}sp(s)} = \frac{109.12(0.01s+1)}{0.0002s^4+0.03124s^3+1.61091s^2+4.311s+110.12}
\] ................................................................. 4.31

\[\text{offset} = C_\infty - C_{id} \] ................................................................. 4.32

\[C_\infty = \lim_{s \to 0} [s \ddot{y}(s)] \] ................................................................. 4.33

\[C_{id} = \text{magnitude of unit step change} = 1 \] ................................................................. 4.34

\[\ddot{y}sp(s) = \frac{1}{s} \] ................................................................. 4.35

\[C_\infty = \lim_{s \to 0} \left[s \frac{109.12(0.01s+1)}{0.0002s^4+0.03124s^3+1.61091s^2+4.311s+110.12} \right] \cdot \frac{1}{s} \] ................................................................. 4.36

\[C_\infty = \frac{2.3}{3.3} = 0.69 \]

\[\varepsilon = 1 - 0.69 = 0.31 \]

Response:

\[G(s) = \pi_t = \frac{109.12}{(0.4s+1)(0.01s+1)(0.01s+1)(3.9s+1)} \] ................................................................. 4.37

\[\varepsilon = 1 - 0.69 = 0.31 \]

Response:
4.2.5 Impulse response of a system

For the system close loop transfer function, different impulse response has been calculated when the system controlled by P, PI, PID controller. The adjustable controller parameters from Routh Hurwitz method, Root locus method and bode method has been used to plot the impulse response.

![Impulse Response Graph](image)

Fig. (4.4): Impulse response of closed loop transfer function for proportional controller by Routh Hurwitz adjustable controller parameters.
4.2.6 System stability and tuning using root locus

Fig. (4.5): Root Locus plot

\[ \omega_{co} = 13.9 \frac{rad}{s} \]

\[ K_u = 321 \]

\[ P_u = \frac{2\pi}{\omega_{co}} = \frac{2 \times 3.14}{3.04} = 0.452 \ldots \]

4.2.6.1 Determination of the adjustable parameters, these are determined using Z-N.

Table (4.2) Ziegler-Nichols adjustable controller parameters for heat exchanger control loop for Root Locus

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>( K_c )</th>
<th>( \tau_c (min) )</th>
<th>( \tau_D (min) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>160.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>144.45</td>
<td>0.38</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>192.6</td>
<td>0.226</td>
<td>0.0565</td>
</tr>
</tbody>
</table>
The system is stable, all elements of the first column were positive and there is no change of sign.

4.2.6.2 Offset investigation:

\[ G(s) = \frac{y(s)}{\bar{y}s.p(s)} = \frac{\pi f}{1+\pi t} \] .................................4.40

\[ \frac{y(s)}{\bar{y}s.p(s)} = \frac{Kc(0.01s+1)}{0.0002s^4+0.03124s^3+1.61091s^2+4.311s+(1+Kc)} \] .................................4.41

\[ Kc = 160 \times 0.5 \text{ from tuning} \]

\[ \frac{y(s)}{\bar{y}s.p(s)} = \frac{160.5(0.01s+1)}{0.0125s^4+0.154s^3+0.71s^2+1.4s+161.5} \] .................................4.42

\[ \text{offset} = C_\infty - C_{id} \] .................................4.43

\[ C_\infty = \lim_{s \to 0} [s\bar{y}(s)] \] .................................4.44

\[ C_{id} = \text{magnitude of unit step change} = 1 \] .................................4.45
\( y_s p(s) = \frac{1}{s} \) .................................................................4.46

\[
C_\infty = \lim_{s \to 0} \left[ s \frac{160.5(0.01s+1)}{0.0125s^4+0.154s^3+0.71s^2+1.4s+161.5} \right] \frac{1}{s} .................................................................4.47
\]

\[
C_\infty = \frac{160.5}{161.5} = 0.67
\]

\[
\varepsilon = 1 - 0.993 = 0.0062
\]

4.2.6.3 Response:

\[
G(s) = \pi l = \frac{160.5}{(0.4s+1)(0.01s+1)(0.01s+1)(3.9s+1)} .................................................................4.48
\]

![Impulse Response](image)

Fig.(4.6): Response of Root Locous for P controller

4.2.6.4 Response of PI &PID controller by Root locous for loop1:

\[
G(s_1) = \frac{K_{c1}(1+\frac{1}{\tau_{i1}})}{(0.4s+1)(0.01s+1)(3.9s+1)(0.01s+1)} .................................................................4.49
\]

\[
G(s_1) = \frac{144.45(1+\frac{1}{0.38})}{(0.4s+1)(0.01s+1)(3.9s+1)(0.01s+1)} = \frac{524.58}{(0.4s+1)(0.01s+1)(3.9s+1)(0.01s+1)} .................................................................4.50
\]

\[
G(s_1) = \frac{524.58}{(0.4s+1)(0.01s+1)(3.9s+1)(0.01s+1)} .................................................................4.51
\]
Fig.(4.7): Impulse response of PI by Root Locous

\[ G(s_1) = \frac{K_c1(1+\frac{1}{T_{i1}s_1}+\tau_D s_1)}{(0.4s+1)(0.01s+1)(3.9s+1)(0.01s+1)} \] \hspace{1cm} 4.52

\[ G(s_1) = \frac{192.6\left(1+\frac{1}{0.226}+0.0565\right)}{(0.4s+1)(0.01s+1)(3.9s+1)(0.01s+1)} = \frac{1055.7}{(0.4s+1)(0.01s+1)(3.9s+1)(0.01s+1)} \] \hspace{1cm} 4.53

Fig.(4.8): Impulse response of PID by Root Locous
4.2.7 Bode methods

\[ \omega_{co} = 11.6 \text{ rad/sec} \]

\[ AR = 1 \]

\[ AR = \frac{K_1 K_2 \cdots K_n}{\sqrt{1 + (\omega \tau_1)^2} \cdot \sqrt{1 + (\omega \tau_2)^2} \cdot \sqrt{1 + (\omega \tau_3)^2}} \] \hspace{1cm} 4.54

\[ G_s = \frac{1Kc}{(0.4s+1)(0.01s+1)(0.01s+1)(3.9s+1)} \] \hspace{1cm} 4.55

\[ AR = \frac{1}{\sqrt{1 + (0.4 + 11.6)^2}} \cdot \frac{1}{\sqrt{1 + (0.01 + 11.6)^2}} \cdot \frac{1}{\sqrt{1 + (0.01 + 11.6)^2}} \cdot \frac{1}{\sqrt{1 + (3.9 + 11.6)^2}} \] \hspace{1cm} 4.56

\[ 1 = \frac{Kc}{4.75 + 1.007 + 45.25 + 45.25} \] \hspace{1cm} 4.57

\[ 1 = \frac{Kc}{96.25} \]

\[ Kc = 96.2 \]

\[ \therefore Kc = 96.2 \]
\[ Ku = 96.2 \]

\[ P_u = \frac{2\pi}{\omega_c} = \frac{2\times 3.14}{11.6} = 0.541 \]

4.2.7.1 Determination of the adjustable parameters, these are determined using Z-N.

Table (4.3): Ziegler-Nichols adjustable controller parameters for heat exchanger control loop for Bode

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>( K_c )</th>
<th>( \tau_i (\text{min}) )</th>
<th>( \tau_D (\text{min}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>0.5Ku</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>0.45Ku</td>
<td>( \frac{pu}{1.2} )</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>0.6Ku</td>
<td>( \frac{pu}{2} )</td>
<td>( \frac{pu}{8} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>( K_c )</th>
<th>( \tau_i (\text{min}) )</th>
<th>( \tau_D (\text{min}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>48.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>43.29</td>
<td>0.451</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>57.72</td>
<td>0.271</td>
<td>0.0676</td>
</tr>
</tbody>
</table>

\( K_c = 48.1 \) for P-action:

\[ 0.0002s^4 + 0.03124s^3 + 1.61091s^2 + 4.311s + 49.1 \]

Checking Stability using Routh:

\[
\begin{bmatrix}
0.0002 & 1.61091 & 49.1 \\
0.03124 & 4.311 & 0 \\
1.583 & 1.22 & 0 \\
3.34 & 0 & 0 \\
49.1 & 0 & 0 \\
\end{bmatrix}
\]
Data of the first column in Routh array:

\[
\begin{bmatrix}
0.0002 \\
0.03124 \\
1.583 \\
3.34 \\
49.1
\end{bmatrix}
\]

The system is stable, all elements of the first column were positive and there is no change of sign.

### 4.2.7.2 Offset investigation:

\[ \frac{y(s)}{\bar{y}sp(s)} = \frac{\pi f}{1+\pi t} \] .................................4.58

\[ \frac{y(s)}{\bar{y}sp(s)} = \frac{Kc(0.01s+1)}{0.0125s^4+0.154s^3+0.71s^2+1.4s+(1+Kc)} \] .................................4.59

\[ Kc = 48.1 \] from tuning

\[ \frac{y(s)}{\bar{y}sp(s)} = \frac{48.1(0.2s+1)}{0.0002s^4+0.03124s^3+1.61091s^2+4.311s+49.1} \] .................................4.60

\[ offset = C_\infty - C_{id} \] .................................4.61

\[ C_\infty = \lim_{s \to 0} [s\bar{y}(s)] \] .................................4.62

\[ C_{id} = \text{magnitude of unit step change} = 1 \] .................................4.63

\[ \bar{y}sp(s) = \frac{1}{s} \] .................................4.64

\[ C_\infty = \lim_{s \to 0} \left[ s \frac{48.1(0.2s+1)}{0.0002s^4+0.03124s^3+1.61091s^2+4.311s+49.1} \right] \frac{1}{s} \] .................................4.65

\[ C_\infty = \frac{48.1}{49.1} = 0.98 \]

\[ \varepsilon = 1 - 0.98 = 0.02 \]
4.2.8 Response of Bode:

Fig. (4.10): Response of Bode.

Loop2: COMPOSITION:

Fig. (4.11): Composition control loop
4.3 Analysis and optimum settings for Loop2(composition).

4.3.1 Routh_Hurwitz Method:
The overall TF:

\[ G(s) = \frac{\pi f}{1 + \pi l} \] ..........................4.66

\[ \pi f = \frac{Kc}{(0.4s+1)(0.01s+1)(3.9s+1)} \] ..........................4.67

\[ \pi l = \frac{Kc}{(0.4s+1)(0.01s+1)(0.02s+1)(3.9s+1)} \] ..........................4.68

\[ 1 + \pi l = \frac{(0.4s+1)(0.01s+1)(0.02s+1)(3.9s+1)+Kc}{(0.4s+1)(0.01s+1)(0.02s+1)(3.9s+1)} \] ..........................4.70

\[ G(s) = \frac{Kc(0.02s+1)}{(0.4s+1)(0.01s+1)(0.02s+1)(3.9s+1)+Kc} \] ..........................4.71

The characteristic equation is:

\[ (0.4s + 1)(0.01s + 1)(0.02s + 1)(3.9s + 1) + Kc = 0 \]

\[ 0.00312s^4 + 0.0469s^3 + 1.654s^2 + 4.31s + (1 + Kc) \]

Number of rows=n+1=4+1=5

\[
\begin{bmatrix}
0.00312 & 1.654 & 1 + Kc \\
0.0469 & 4.31 & 0 \\
1.625 & 1 + Kc & 0 \\
7.005163 - 0.0469(1 + Kc) & 0 & 0 \\
1.625 & 1 + Kc & 0 \\
\end{bmatrix}
\]

For the system to be critically stable the row number n is equal to zero:

\[ 7.005163 - 0.0469(1 + Kc) = 0 \] ..........................4.72

\[ 7.005163 - 0.0469 - 0.0469Kc = 0 \] ..........................4.73

\[ Kc = \frac{6.96}{0.0469} = 148.36 \] ..........................4.74

The ultimate gain, \( K_u = 148.36 \)
4.3.2 Direct substitution method:
To find the crossover frequency, \( \omega_{co} \)

Set \( s = i\omega \)

\[
0.000312s^4 + 0.0469s^3 + 1.654s^2 + 4.31s + (1 + K_c) \quad \cdots \quad 4.75
\]

\[
0.000312\omega^4 - 0.0469i\omega^3 - 1.654\omega^2 + 4.31i\omega + (1 + K_c)
\]

\[
Re = 0.000312\omega^4 - 1.654\omega^2 + (1 + K_c) \quad \cdots \quad 4.76
\]

Taking the imaginary part

\[
im = 4.31\omega - 0.0469\omega^3
\]

\[
im = \omega(4.31 - 0.0469\omega^2) \quad \cdots \quad 4.77
\]

\[
4.31 - 0.0469\omega^2 = 0
\]

\[
4.31 = 0.0469\omega^2
\]

\[
\omega_{co} = 9.59 \, \frac{rad}{sec}
\]

Taking the real part

\[
0.000312\omega^4 - 1.654\omega^2 + (1 + K_c) = 0
\]

\[
0.000312(9.59)^4 - 1.654(9.59)^2 + (1 + K_c) = 0
\]

\[
-K_c = -149.5
\]

\[
K_c = 149.5
\]

\[
Pu = \frac{2\pi}{\omega_{co}} = \frac{2\pi}{9.59} = 0.656\, sec
\]

4.3.3 Determination of the adjustable parameters, these are determined using Z-N.
Table(4.4): Ziegler-Nichols adjustable controller parameters for composition control loop for Routh Locous
<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Kc</th>
<th>$\tau_i (\text{min})$</th>
<th>$\tau_D (\text{min})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>0.5Ku</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>0.45Ku</td>
<td>$\frac{pu}{1.2}$</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>0.6Ku</td>
<td>$\frac{pu}{2}$</td>
<td>$\frac{pu}{8}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Kc</th>
<th>$\tau_i (\text{min})$</th>
<th>$\tau_D (\text{min})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>74.75</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>67.275</td>
<td>5.233</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>89.7</td>
<td>3.14</td>
<td>0.785</td>
</tr>
</tbody>
</table>

K=74.75 substituting for the value of Kc=74.75 for P-action:

$$0.000312s^4 + 0.0469s^3 + 1.654s^2 + 4.31s + 75.75 = 0$$

Checking Stability using Routh:

$$\begin{bmatrix} 0.000312 & 1.654 & 75.75 \\ 0.0469 & 4.31 & 0 \\ 1.6253 & 75.75 & 0 \\ 2.2124 & 0 & 0 \\ 75.75 & 0 & 0 \end{bmatrix}$$

Data of the first column in Routh array:

$$\begin{bmatrix} 0.000312 \\ 0.0469 \\ 1.6253 \\ 2.2124 \\ 75.75 \end{bmatrix}$$

The system is stable.

**4.3.4 Offset investigation:**

$$G(s) = \frac{\bar{y}(s)}{\bar{y}_s p(s)} = \frac{\pi f}{1 + \pi l}$$

.........................................................4.78
\[
\frac{\ddot{y}(s)}{ys.p(s)} = \frac{Kc(0.02s+1)}{0.000312s^4+0.0469s^3+1.654s^2+4.31s+(1+4Kc)}
\]  

\[Kc = 74.75 \text{ from tuning}\]

\[
\frac{\ddot{y}(s)}{ys.p(s)} = \frac{74.75(0.02s+1)}{0.000312s^4+0.0469s^3+1.654s^2+4.31s+75.75}
\]

\[\text{offset} = C_\infty - C_{id}\]

\[C_\infty = \lim_{s \to 0} [s\ddot{y}(s)]\]

\[C_{id} = \text{magnitude of unit step change} = 1\]

\[\ddot{ys}.p(s) = \frac{1}{s}\]

\[C_\infty = \lim_{s \to 0} \left[ s \frac{74.75(0.02s+1)}{0.000312s^4+0.0469s^3+1.654s^2+4.31s+75.75} \right] \frac{1}{s}\]

\[\varepsilon = 1 - 0.99 = 0.01\]

**4.3.5 Response:**

\[G(s) = \left[ \frac{74.75(0.02s+1)}{0.000312s^4+0.0469s^3+1.654s^2+4.31s+75.75} \right].\]
4.3.6 System stability and tuning using root locus

![Root locus plot](image)

Figure(4.13)Root locus plot

Kc = 164

\[\omega_{co} = 9.92 \text{ rad/ sec}\]

\[P_u = \frac{2\pi}{\omega_{co}} = \frac{2 \times 3.14}{9.92} = 0.633\]

4.3.7 Determination of the adjustable parameters, these are determined using Z-N.

Table(4.5): Ziegler-Nichols adjustable controller parameters for composition control loop for Root Locous

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Kc</th>
<th>(\tau_i) (min)</th>
<th>(\tau_D) (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>0.5Ku</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>0.45Ku</td>
<td>(\frac{pu}{1.2})</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>0.6Ku</td>
<td>(\frac{pu}{2})</td>
<td>(\frac{pu}{8})</td>
</tr>
</tbody>
</table>
Type of controller | Kc  | $\tau_i (min)$ | $\tau_d (min)$ |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>82</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>73.8</td>
<td>0.5275</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>98.4</td>
<td>0.3165</td>
<td>0.07915</td>
</tr>
</tbody>
</table>

$K_c = 183.5$ substituting for the value of $K_c = 183.5$ for P-action:

$$0.000312s^4 + 0.0469s^3 + 1.654s^2 + 4.31s + 83 = 0$$

Checking Stability using Routh:

$$\begin{bmatrix}
0.000312 & 1.654 & 83 \\
0.0469 & 4.31 & 0 \\
1.625 & 83 & 0 \\
1.915 & 0 & 0 \\
83 & 0 & 0
\end{bmatrix}$$

Data of the first column in Routh array:

$$\begin{bmatrix}
0.000312 \\
0.0469 \\
1.625 \\
1.915 \\
83
\end{bmatrix}$$

The system is stable.

4.3.8 Offset investigation:

$$G(s) = \frac{y(s)}{y.s.p(s)} = \frac{\pi f}{1+\pi l} \rightarrow \frac{y(s)}{y.s.p(s)} = \frac{K_c(0.02s+1)}{0.000312s^4 + 0.0469s^3 + 1.654s^2 + 4.31s + 83(1+K_c)}$$

$K_c = 82$ from tuning

$$\frac{y(s)}{y.s.p(s)} = \frac{82(0.02s+1)}{0.000312s^4 + 0.0469s^3 + 1.654s^2 + 4.31s + 83}$$

$offset = C_{\infty} - C_{id}$
\[ C_\infty = \lim_{s \to 0} [s \ddot{y}(s)] \] ..................................................4.90

\[ C_{id} = \text{magnitude of unit step change} = 1 \] ..................................................4.91

\[ \ddot{y} s. p(s) = \frac{1}{s} \] ..................................................4.92

\[ C_\infty = \lim_{s \to 0} \left[ s \frac{82(0.02s+1)}{0.000312s^4+0.0469s^3+1.654s^2+4.31s+83} \right] \frac{1}{s} \] ..................................................4.93

\[ C_\infty = \frac{82}{83} = 0.99 \]

\[ \varepsilon = 1 - 0.99 = 0.01 \]

Figure(4.14): Response of P controller using Root locus method.

**4.3.9 Response of PI & PID controller by Root locus for loop2:**

\[ G_{c1} = \frac{K_{c1} \left( 1 + \frac{1}{1/0.55} \right)}{(0.4s+1)(0.01s+1)(3.9s+1)(0.02s+1)} \] ..................................................4.94

\[ G_{c1} = \frac{73.8 \left( 1 + \frac{1}{0.527s} \right)}{(0.4s+1)(0.01s+1)(3.9s+1)(0.02s+1)} = \frac{213.7}{(0.4s+1)(0.01s+1)(3.9s+1)(0.02s+1)} \] ..................................................4.100
\[ G(s_1) = \frac{213.7}{(0.4s+1)(0.01s+1)(3.9s+1)(0.02s+1)} \] \hspace{2cm} \text{Figure (4.15)}: response of Root locus for PI controller.

\[ G(s_1) = \frac{K_c (1 + \frac{1}{0.3165} + \tau_D s_1)}{(0.4s+1)(0.01s+1)(3.9s+1)(0.02s+1)} \] \hspace{2cm} \[ G(s_1) = \frac{984 (1 + \frac{1}{0.3165} + 0.07915)}{(0.4s+1)(0.01s+1)(3.9s+1)(0.02s+1)} = \frac{417.08}{(0.4s+1)(0.01s+1)(3.9s+1)(0.02s+1)} \]
Figure(4.16): response of Root locus for PID controller.

4.3.10 System tuning and stability using bode diagram

Figure(4.17) Bode plot
\[ \omega_{co} = 9.47 \frac{\text{rad}}{\text{sec}} \]

\[ AR = 1 \]

\[ AR = \frac{K_1K_2...K_n}{\sqrt{1+(\omega \tau_1)^2} \cdot \sqrt{1+(\omega \tau_2)^2} \cdot \sqrt{1+(\omega \tau_3)^2}} \]

\[ G_s = \frac{K_c}{(0.4s+1)(0.01s+1)(0.02s+1)(3.9s+1)} \]

\[ AR = \frac{1}{\sqrt{1+(0.4+9.47)^2}} \cdot \frac{1}{\sqrt{1+(0.01+9.47)^2}} \cdot \frac{1}{\sqrt{1+(0.02+9.47)^2}} \cdot \frac{1}{\sqrt{1+(3.9+9.47)^2}} \]

\[ 1 = \frac{K_c}{3.9178+1.00447+1.01778+36.947} \]

\[ 1 = \frac{K_c}{147.89} \]

\[ K_c = 147.89 \]

\[ \therefore K_c = 147.89 \]

\[ \therefore K_u = 147.89 \]

\[ P_u = \frac{2\pi}{\omega_{co}} = \frac{2 \cdot 3.14}{9.47} = 0.66 \]

4.3.10.1 Determination of the adjustable parameters, these are determined using Z-N.

Table(4.6): Ziegler-Nichols adjustable controller parameters for composition control loop for Bode.

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Kc</th>
<th>(\tau_I) (min)</th>
<th>(\tau_D) (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>0.5Ku</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>0.45Ku</td>
<td>(\frac{pu}{1.2})</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>0.6Ku</td>
<td>(\frac{pu}{2})</td>
<td>(\frac{pu}{8})</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Kc</th>
<th>$\tau_i$ (min)</th>
<th>$\tau_D$ (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>73.945</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>66.55</td>
<td>0.55</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>88.73</td>
<td>0.33</td>
<td>0.0825</td>
</tr>
</tbody>
</table>

$K_c = 73.945$ substituting for the valve of, $K_u = 73.945$ for P-action:

$$0.000312s^4 + 0.0469s^3 + 1.654s^2 + 4.31s + 74 = 0$$

Checking Stability using Routh:

$$
\begin{bmatrix}
0.000312 & 1.654 & 74  \\
0.0469  & 4.31  & 0  \\
0.428 & 4.56 & 0  \\
0.370 & 0 & 0  \\
4.56 & 0 & 0
\end{bmatrix}
$$

Data of the first column in Routh array:

$$
\begin{bmatrix}
0.000312  \\
0.0469  \\
1.625  \\
4.178  \\
74
\end{bmatrix}
$$

The system is stable .

**4.3.10.2 Offset investigation:**

$$G(s) = \frac{\bar{y}(s)}{\bar{y}_s p(s)} = \frac{\pi f}{1 + \pi^2} \hspace{1cm} \text{.........................................................4.108}$$

$$\frac{\bar{y}(s)}{\bar{y}_s p(s)} = \frac{74(0.02s + 1)}{0.000312s^4 + 0.0469s^3 + 1.654s^2 + 4.31s + 74 + (1 + 4K_c)} \hspace{1cm} \text{.........................................................4.109}$$

$K_c = 0.4$ from tuning

$$\frac{\bar{y}(s)}{\bar{y}_s p(s)} = \frac{74(0.02s + 1)}{0.000312s^4 + 0.0469s^3 + 1.654s^2 + 4.31s + 75} \hspace{1cm} \text{.........................................................4.110}$$
offset = $C_\infty - C_{id}$ .................................................................4.111

$C_\infty = \lim_{s \to 0}[s\bar{y}(s)]$ .........................................................4.112

$C_{id} = \text{magnitude of unit step change} = 1$ .........................4.113

$\bar{y}s.p(s) = \frac{1}{s}$ .................................................................4.114

$C_\infty = \lim_{s \to 0} \left[ s \frac{74(0.02s+1)}{0.000312s^4+0.0469s^3+1.654s^2+4.31s+75} \right] \frac{1}{s}$ .........................................................4.115

$C_\infty = \frac{74}{75} = 0.98$

$\varepsilon = 1 - 0.98 = 0.013$

Figure (4.19): response of Bode plot

4.4 Comparison between the adjustable parameter using different method of tuning

Loop 1:

Table (4.7): Comparison between the adjustable parameter using different method of tuning for heat exchanger control loop 1.
Table (4.8): Comparison between the adjustable parameter using different method of tuning for composition control loop 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Direct substitution method</th>
<th>Root locus method</th>
<th>Bode plot method</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Kc1 )</td>
<td>109.12</td>
<td>160.5</td>
<td>48.1</td>
</tr>
<tr>
<td>( \tau_{I1} )</td>
<td>2.33</td>
<td>0.38</td>
<td>0.451</td>
</tr>
<tr>
<td>( \tau_{D1} )</td>
<td>0.35</td>
<td>0.0565</td>
<td>0.0676</td>
</tr>
</tbody>
</table>

Loop 2:

Table (4.9): Comparison between the offset investigations using different method of tuning for composition control loop 2.

<table>
<thead>
<tr>
<th>Offset</th>
<th>Direct substitution method</th>
<th>Root locus method</th>
<th>Bode plot method</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \epsilon_1 )</td>
<td>0.31</td>
<td>0.01</td>
<td>0.02</td>
</tr>
</tbody>
</table>

It is noted in the above two tables that:

- By comparing the adjustable controller parameters of the three methods (Routh Hurwitz method, direct substitution, Root Locus and Bode method) it is clear that Root Locus method adjustable control parameters is the best way to design the control systems.

4.5 Comparison between the offset investigations using different method of tuning

Table (4.9): Comparison between the offset investigations using different method of tuning

Offset for loop 1:
Table (4.10) Comparison between the offset investigations using different method of tuning Offset for loop 2:

<table>
<thead>
<tr>
<th>Offset</th>
<th>Direct substitution method</th>
<th>Root locus method</th>
<th>Bode plot method</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_2$</td>
<td>0.01</td>
<td>0.01</td>
<td>0.13</td>
</tr>
</tbody>
</table>

- It is clear that Root Locous for the proportional action is the lowest offset.

### 4.6 Comparison between the three type of controller

Table (4.11) Comparison between the three type of controller by Root Locous for loop 1.

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Overshoot%</th>
<th>Period time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>31.7%</td>
<td>1.06</td>
</tr>
<tr>
<td>PI</td>
<td>104%</td>
<td>1.01</td>
</tr>
<tr>
<td>PID</td>
<td>208%</td>
<td>1.09</td>
</tr>
</tbody>
</table>

From the table PID controller should be eliminated because it had a highest overshoot and period time, the comparison could be done between P & PID. P controller is the lowest overshoot 31.7% and period time 1.06 so it's the best one.

Table (4.12) Comparison between the three type of controller by Root Locous for loop 2.

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Overshoot</th>
<th>Period time</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>16.4%</td>
<td>1.01</td>
</tr>
<tr>
<td>PI</td>
<td>42.2%</td>
<td>0.973</td>
</tr>
<tr>
<td>PID</td>
<td>82.3%</td>
<td>0.989</td>
</tr>
</tbody>
</table>

From the table above the lowest period time 1.01 and lowest overshoot 16.4% existed in proportional controller.
4.7 SCADA system

Fig. (4.20) SCADA control loop

The overall TF:

\[ G(s) = \frac{\pi f}{1 + \pi l} \] ................................................................. 4.102

\[ \pi f = \frac{Kc}{(0.4s+1)(0.01s+1)(3.9s+1)} \] ................................................................. 4.103

\[ \pi l = \frac{Kc}{(0.4s+1)(0.01s+1)(0.01s+1)(3.9s+1)} \]

\[ 1 + \pi l = \frac{(0.4s+1)(0.01s+1)(0.01s+1)(3.9s+1)+Kc}{(0.4s+1)(0.01s+1)(0.01s+1)(3.9s+1)} \] ................................................................. 4.104

\[ G(s) = \frac{Kc(0.01s+1)}{(0.4s+1)(0.01s+1)(0.01s+1)(3.9s+1)+2Kc} \] ................................................................. 4.105

The characteristic equation is:

\[ (0.4s + 1)(0.5s + 1)(0.2s + 1)(3.9s + 1) + (1 + Kc_1Kc_2) = 0 \]

\[ 0.0002s^4 + 0.03124s^3 + 1.61091s^2 + 4.311s + (1 + Kc_1Kc_2) \]

Number of rows = n+1=4+1=5
For the system to be critically stable the row number $n$ is equal to zero:

$$6.8255 - 0.0312 (1 + Kc_1 Kc_2) = 0$$

$$6.8255 - 0.0312 - 0.0312 Kc_1 Kc_2 = 0$$

$$226.6 Kc_1 = \frac{6.79}{0.0312} = 217.76$$

$$Kc_1 = 0.96$$

The ultimate gain, $Ku$ for SCADA=0.96

### 4.8 Digital Controller Design

![Digital Temperature Controller Diagram](image_url)
the continous controller, can be replaced by a digital controller that performe same control task as the continous controller.

Fig.(4.22) digital temperature controller connected with SCADA system.
Discussion

The control strategy of the crude oil temperature and viscosity in all process were drown as shown in fig(3.1). Then each process was temperature and viscosity controlled. The transfer functions were identified, the overall transfer functions were obtained from the block diagram and consequently the characteristic equations were obtained. The polynomial s in S were taken and stability was carried out using Routh test to obtain the ultimate gain $K_u$ period $P_u$ then Ziegler-Nichols tuning method was used to determine the adjustable parameters($K_c, \tau_I, \tau_D$) these were used to plot the impulse response of the system. By comparing the adjustable controller parameters of the four methodes (Routh Hurwitz method, direct substitution, Root Locus and Bode method) it is clear that Root Locus method adjustable control parameters is the best way to design the control systems. And by comparing the overshoot for P,PI&PID controller it found that Proportional controller gives the lowest overshoot and it is the suitable type for the system.
Chapter five
Conclusion and Recommendation

5.1 Conclusion

- Control configuration was made, transfer functions were determined and so were the characteristics equations.
- The stability analysis and tuning were found using Routh, Direct substitution, Root Locus, and Bode.
- Root Locus, Bode tuning method were used to determine the adjustable parameters and the impulse response was made accordingly.
- The comparison between three methods were done, and found that Root Locus was the best one for the system.
- The comparison between the lowest overshoot and period time for the three type of controller P, PI, & PID was done, it found that proportional controller gave the lowest overshoot.

5.2 Recommendation

- The control system should be converted to digital controller system.
- Auto tuning should be done.
- Fuzzy control might be used for more accuracy.
- SCADA system is very useful in remote areas, and should be applied.
REFERENCES

6. Cheng, X. and Sharma, R (2002). Rheological study on marine terminal samples, as received Nile Blend and flushing diesel, report to CNPOC.
9. KSCC, (2001). Application of pour point depressant in Muglad development export crude, King Shain product CNPC, report to CNPOC.
29. Pao C. Chau (2001). Chemical Process Control: A First Course with MATLAB, Web Support (MATLAB outputs of text examples and MATLAB sessions, references, and supplementary notes) is available at the CENG 120 homepage. Go to http://courses.ucsd.edu and find CENG 120.
APPENDICES

Appendix(A)

Loop(1)

- Response of Routh method

MATLAB input:

```matlab
>> num=[109.12];
>> a=conv([0.4 1],[0.01 1]);
>> b=conv([0.01 1],[3.9 1]);
>> den=conv(a,b);
>> impulse(num,den);
```

- Root locus analyz:

```matlab
>> num=[1];
>> a=conv([0.4 1],[0.01 1]);
>> b=conv([0.01 1],[3.9 1]);
>> den=conv(a,b);
>> rlocus(num,den);
```

- Response of Root locus

```matlab
>> num=[160.5];
>> a=conv([0.4 1],[0.01 1]);
>> b=conv([0.01 1],[3.9 1]);
>> den=conv(a,b);
>> impulse(num,den);
```

- Response of PI by Root Locous for loop1

```matlab
>> num=[524.58];
```
>> a=conv([0.4 1],[0.01 1]);
>> b=conv([0.01 1],[3.9 1]);
>> den=conv(a,b);
>> impulse(num,den)

- Response of PID by Root Locus

>> num=[105.7];
>> a=conv([0.4 1],[0.01 1]);
>> b=conv([0.01 1],[3.9 1]);
>> den=conv(a,b);
>> impulse(num,den)

- Bode plot:

>> num=[1];
>> a=conv([0.4 1],[0.01 1]);
>> b=conv([0.01 1],[3.9 1]);
>> den=conv(a,b);
>> bode(num,den)

- Response of Bode

Matlab input
>> num=[48.1];
>> a=conv([0.4 1],[0.01 1]);
>> b=conv([0.01 1],[3.9 1]);
>> den=conv(a,b);
>> impulse(num,den);
Appendix (B)

Loop (2)

- Response of Routh method

Matlab input

```matlab
>> num= [74.75];
>> a= conv([0.4 1],[0.5 1]);
>> b= conv([0.2 1],[0.1 1]);
>> den= conv(a,b);
>> impulse(num,den);
```

- Root locus input

```matlab
>> num=[1];
>> a= conv([0.4 1],[0.01 1]);
>> b= conv([0.02 1],[3.9 1]);
>> den= conv(a,b);
>> rlocus(num,den)
```

- Response of Root locus

```matlab
>> num=[83];
>> a= conv([0.4 1],[0.01 1]);
>> b= conv([0.02 1],[3.9 1]);
>> den= conv(a,b);
>> impulse(num,den);
```

- Response of PI by Root Locus for loop2
num=[213.7];
a=conv([0.4 1],[0.01 1]);
b=conv([0.02 1],[3.9 1]);
den=conv(a,b);
impulse(num,den);

- Response of PI Dby Root Locus for loop2
num=[417.08];
a=conv([0.4 1],[0.01 1]);
b=conv([0.02 1],[3.9 1]);
den=conv(a,b);
impulse(num,den);

- Bode input:
num=[1];
a=conv([0.4 1],[0.01 1]);
b=conv([0.02 1],[3.9 1]);
den=conv(a,b);
bode(num,den)

- Response of Bode plot
num=[74];
a=conv([0.4 1],[0.011]);
b=conv([0.02 1],[3.9 1]);
den=conv(a,b);
impulse(num,den)