IDC TECHNOLOGIES

Technology Training that Works

Presents

Practical Tuning of Industrial Control Loops

Revision 7

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Acknowledgements

IDC Technologies expresses its sincere thanks to all those engineers and technicians on our training workshops who freely made available their expertise in preparing this manual.

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Who is IDC Technologies?

IDC Technologies is a specialist in the field of industrial communications, telecommunications, automation and control and has been providing high quality training for more than six years on an international basis from offices around the world.

IDC consists of an enthusiastic team of professional engineers and support staff who are committed to providing the highest quality in their consulting and training services.

The Benefits to you of Technical Training Today

The technological world today presents tremendous challenges to engineers, scientists and technicians in keeping up to date and taking advantage of the latest developments in the key technology areas.

- The immediate benefits of attending IDC workshops are:
- Gain practical hands-on experience
- Enhance your expertise and credibility
- Save $$$s for your company
- Obtain state of the art knowledge for your company
- Learn new approaches to troubleshooting
- Improve your future career prospects

The IDC Approach to Training

All workshops have been carefully structured to ensure that attendees gain maximum benefits. A combination of carefully designed training software, hardware and well written documentation, together with multimedia techniques ensure that the workshops are presented in an interesting, stimulating and logical fashion.

IDC has structured a number of workshops to cover the major areas of technology. These courses are presented by instructors who are experts in their fields, and have been attended by thousands of engineers, technicians and scientists world-wide (over 11,000 in the past two years), who have given excellent reviews. The IDC team of professional engineers is constantly reviewing the courses and talking to industry leaders in these fields, thus keeping the workshops topical and up to date.

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Technical Training Workshops

IDC is continually developing high quality state of the art workshops aimed at assisting engineers, technicians and scientists. Current workshops include:

Instrumentation & Control

- Practical Automation and Process Control using PLC's
- Practical Data Acquisition using Personal Computers and Standalone Systems
- Practical On-line Analytical Instrumentation for Engineers and Technicians
- Practical Flow Measurement for Engineers and Technicians
- Practical Intrinsic Safety for Engineers and Technicians
- Practical Safety Instrumentation and Shut-down Systems for Industry
- Practical Process Control for Engineers and Technicians
- Practical Programming for Industrial Control – using (IEC 1131-3;OPC)
- Practical SCADA Systems for Industry
- Practical Boiler Control and Instrumentation for Engineers and Technicians
- Practical Process Instrumentation for Engineers and Technicians
- Practical Motion Control for Engineers and Technicians
- Practical Communications, SCADA & PLC's for Managers

Communications

- Practical Data Communications for Engineers and Technicians
- Practical Essentials of SNMP Network Management
- Practical Field Bus and Device Networks for Engineers and Technicians
- Practical Industrial Communication Protocols
- Practical Fibre Optics for Engineers and Technicians
- Practical Industrial Networking for Engineers and Technicians
- Practical TCP/IP & Ethernet Networking for Industry
- Practical Telecommunications for Engineers and Technicians
- Practical Radio & Telemetry Systems for Industry
- Practical Local Area Networks for Engineers and Technicians
- Practical Mobile Radio Systems for Industry

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Electrical

- Practical Power Systems Protection for Engineers and Technicians
- Practical High Voltage Safety Operating Procedures for Engineers & Technicians
- Practical Solutions to Power Quality Problems for Engineers and Technicians
- Practical Communications and Automation for Electrical Networks
- Practical Power Distribution
- Practical Variable Speed Drives for Instrumentation and Control Systems

Project & Financial Management

- Practical Project Management for Engineers and Technicians
- Practical Financial Management and Project Investment Analysis
- How to Manage Consultants

Mechanical Engineering

- Practical Boiler Plant Operation and Management for Engineers and Technicians
- Practical Centrifugal Pumps – Efficient use for Safety & Reliability

Electronics

- Practical Digital Signal Processing Systems for Engineers and Technicians
- Practical Industrial Electronics Workshop
- Practical Image Processing and Applications
- Practical EMC and EMI Control for Engineers and Technicians

Information Technology

- Personal Computer & Network Security (Protect from Hackers, Crackers & Viruses)
- Practical Guide to MCSE Certification
- Practical Application Development for Web Based SCADA

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Comprehensive Training Materials

Workshop Documentation

All IDC workshops are fully documented with complete reference materials including comprehensive manuals and practical reference guides.

Software

Relevant software is supplied with most workshops. The software consists of demonstration programs which illustrate the basic theory as well as the more difficult concepts of the workshop.

Hands-On Approach to Training

The IDC engineers have developed the workshops based on the practical consulting expertise that has been built up over the years in various specialist areas. The objective of training today is to gain knowledge and experience in the latest developments in technology through cost effective methods. The investment in training made by companies and individuals is growing each year as the need to keep topical and up to date in the industry which they are operating is recognized. As a result, the IDC instructors place particular emphasis on the practical hands-on aspect of the workshops presented.

On-Site Workshops

In addition to the quality of workshops which IDC presents on a world-wide basis, all IDC courses are also available for on-site (in-house) presentation at our clients' premises. On-site training is a cost effective method of training for companies with many delegates to train in a particular area. Organizations can save valuable training $$$'s by holding courses on-site, where costs are significantly less. Other benefits are IDC's ability to focus on particular systems and equipment so that attendees obtain only the greatest benefits from the training.

All on-site workshops are tailored to meet with clients training requirements and courses can be presented at beginners, intermediate or advanced levels based on the knowledge and experience of delegates in attendance. Specific areas of interest to the client can also be covered in more detail. Our external workshops are planned well in advance and you should contact us as early as possible if you require on-site/customized training. While we will always endeavor to meet your timetable preferences, two to three month's notice is preferable in order to successfully fulfil your requirements. Please don't hesitate to contact us if you would like to discuss your training needs.

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Customized Training

In addition to standard on-site training, IDC specializes in customized courses to meet client training specifications. IDC has the necessary engineering and training expertise and resources to work closely with clients in preparing and presenting specialized courses.

These courses may comprise a combination of all IDC courses along with additional topics and subjects that are required. The benefits to companies in using training are reflected in the increased efficiency of their operations and equipment.

Training Contracts

IDC also specializes in establishing training contracts with companies who require ongoing training for their employees. These contracts can be established over a given period of time and special fees are negotiated with clients based on their requirements. Where possible, IDC will also adapt courses to satisfy your training budget.

References from various international companies to whom IDC is contracted to provide on-going technical training are available on request.

Some of the thousands of Companies worldwide that have supported and benefited from IDC workshops are:

Alcoa, Allen-Bradley, Altona Petrochemical, Aluminum Company of America, AMC Mineral Sands, Amgen, Arco Oil and Gas, Argyle Diamond Mine, Associated Pulp and Paper Mill, Bailey Controls, Bechtel, BHP Engineering, Caltex Refining, Canon, Chevron, Coca-Cola, Colgate-Palmolive, Conoco Inc, Dow Chemical, ESKOM, Exxon, Ford, Gillette Company, Honda, Honeywell, Kodak, Lever Brothers, McDonnell Douglas, Mobil, Modicon, Monsanto, Motorola, Nabisco, NASA, National Instruments, National Semi-Conductor, Omron Electric, Pacific Power, Pirelli Cables, Proctor and Gamble, Robert Bosch Corp, Siemens, Smith Kline Beecham, Square D, Texaco, Varian, Warner Lambert, Woodside Offshore Petroleum, Zener Electric

Table of Contents

Chapter 5— Cascade control 123

Chapter 6— Feedforward and ratio control 139

Chapter 7— Long process deadtime in closed loop control 167

Chapter 8— Auto tuning and self tuning controllers 175

Foreword

This is a comprehensive manual covering the essentials of tuning and troubleshooting industrial control loops, ranging from the simplest to the most complex.

The manual (and associated) training workshop is designed to train you in the latest procedures for the tuning of industrial control loops using a minimum of mathematics and formula. Tuning controllers is an exact science that requires precise configuration of the process controller, using the correct procedures. Tuning takes place when the controller is set up correctly.

The aim of the workshop is to provide you with the skills required how to tune a controller for optimum operation. An optimally tuned loop is critical for a wide variety of industries ranging from food processing, chemical manufacturing, oil refineries, pulp and paper mills, mines and steel mines. Although tuning rules are designed to give reasonably tight control, this may not always be the objective. Some thought needs to be given when re-tuning a loop as to whether the additional effort is justified, since there may be other issues that are the cause of poor control. These issues are discussed in some detail in the manual. At the end of studying the manual, it is hoped that you will have the skills to troubleshoot and tune a wide variety of process loops.

At the conclusion of reading this manual (and hopefully attending the associated training workshop), you will:

- Know the fundamentals of tuning loops – both open and closed loop
- Get the best PID settings right first time
- Know where to troubleshoot to achieve optimally tuned control loops
- Be able to apply step-by-step descriptions of the best field-proven tuning procedures
- Know the typical procedures for troubleshooting tuning problems
- Tune more control loops in less time with consistently excellent results
- Be able to apply 28 practical rules of thumb for tuning systems
- Be proficient at tuning with a detailed knowledge of:
  - Open loop tuning
  - Closed loop tuning (including such classics as Ziegler Nichols Tuning and Lambda Tuning)

- Be able to determine the minimum settling time for a control loop
- Know the optimum amount of filtering or dampening to apply to the measurement
- Know why and how to size valves for best control loop performance
- Be able to handle problems such as valve hysteresis, stiction and non-linearities
- Be able to tune complex loops ranging from cascade to feedforward
- Know when to use derivative control for the best tuned loop

This book is intended for engineers and technicians who are:

- Instrumentation and Control Engineers/technicians
- Process Control Engineers
- Electrical Engineers
- System Integrators
- Designers
- Design Engineers
- Systems Engineers
- Operators monitoring and controlling processes
- Automation Engineers
- Consulting Engineers
- Plant Managers
- Shift Electricians

A basic knowledge of electrical concepts and some knowledge of instrumentation would be useful in reading this book.

The structure of the manual is listed below.

Foreword

Chapter 1 Introduction

An overview of the manual summarizing the material covered in the manual.

Chapter 2 Fundamentals of control systems

An outline of the basic principles underpinning process control including open and closed loop control, stability, reverse and direct acting loops and cascade and feedforward control.

Chapter 3 Fundamentals of tuning of PID controllers

A review of the basic principles of tuning loops including open and closed loop control.

Chapter 4 Different tuning rules available

A discussion of the other tuning rules that can be used to tune a loop.

Chapter 5 Tuning of valves

The important issues of tuning valves such as hysteresis and stiction.

Chapter 6 Cascade control

The structure and tuning of cascade loops.

Chapter 7 Feedforward and ratio control

A review of the concept of feedforward and ratio control and how to tune controllers.

Chapter 8 More complex systems

A brief discussion on some of the more complex methods of control.

Chapter 9 Long process deadtime in closed loop control

The issues of process loops with deadtime and tuning them using Smith Predictors.

Chapter 10 Adaptive and self tuning controllers

The operation and use of adaptive or self tuning controllers.

Chapter 11 Good practice and troubleshooting in tuning

Good practice tuning rules for general process control loops such as flow, level, temperature and cascade variations.

Appendix A Glossary

A glossary of all the terms used in process control and tuning of loops.

Appendix B Instrumentation

A brief review of the main items of instrumentation for measuring flow, temperature, pressure and level.

Appendix C Laplace transforms and block diagrams

The basic Laplace transforms and block manipulation techniques.

Appendix D Digital control principles

A brief consideration of the main principles in converting PID control from an analog based system to one that is discrete and digital based.

Appendix E Real and ideal PID controllers

A review of the differences between the ideal (very process noise sensitive) PID blocks and the “field hardened” real PID controller.

Appendix F Basic principles of valves and actuators

A discussion the main types of valves and their successful operation.

Appendix G Practical sessions

A summary of the practical sessions undertaken in the two day course.

1

Introduction

Learning objectives

As a result of studying this chapter, you should be able to:

- Describe the three different types of processes
- Indicate the meaning of a time constant
- Describe the meaning of process variable, setpoint and output
- List the different modes of operation of a control system

1.1 Introduction

In principle, most process control systems consist of a control loop, comprising four main functions, these being:

- A measurement of the state or condition of a process
- A controller calculating an action based on this measured value against a pre-set or control value (setpoint)
- A signal with a value that represents the result of this calculation being fed back from the controller to the process, which is to manipulate the process action
- The process itself reacting to this signal, and changing its state or condition.

In this manual, we will discuss the measurement of a process, control calculations based on this measurement and how the final result is used. Every process is unique and has different characteristics. Therein lies the first problem: the objective to achieve tighter and close control of the process. This places us in a dilemma as we do not know what that process is, but we cannot ignore it. The second problem is to identify where to start when the entire process is a loop. Do we start with measurement, or the controller? Fortunately, a solution to the first problem, that of the unknown process, gives us the solution to the second problem.

All processes must have a set of common parameters and dynamics; if they don't, every type of controller would have to be different and no common boundaries would exist.

The dynamics of each process, their type and magnitude, have to be understood before any attempt can be made in selecting the type of measuring device(s), the type of control system and finally the type of final control element.

Let us start by examining the component parts of the more important dynamics that are common to all process functions. This will be the topic covered in the next few sections of this chapter, and upon completion we should be able to draw a simple block for any process system. For example, we would be able to say "It is a system with capacitive and inertial properties, and as such we can expect it to perform in the following way", regardless of the precise details of the process.

To visualize the behavior of a system, block diagrams can be used to provide a visual description of the components. The two main symbols used are the circle and the rectangular block as shown in Figure 1.1.

The circle represents algebraic addition and subtraction. It is always entered by two lines but exited by only one line.

The rectangular block represents algebraic multiplication and division. It is entered and exited by only one line. The output is the product of the system function, which is symbolized inside the block, with the input.

The system function is the symbolic representation of how an input change affects the output for a particular process component.

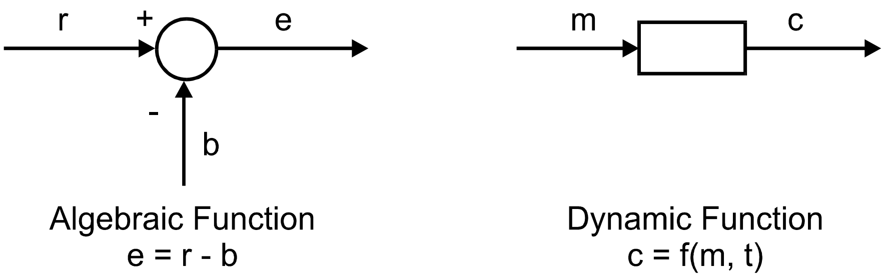


Figure 1.1
Diagram of the summer and gain blocks

The steady state and dynamic behavior of a system can be determined by solving the differential equation that represents the system. Solving the differential equations is time consuming and a tedious task. The Laplace transformation technique is used for solving differential equations. In process control, Laplace transforms are commonly used to determine the responses to process disturbances.

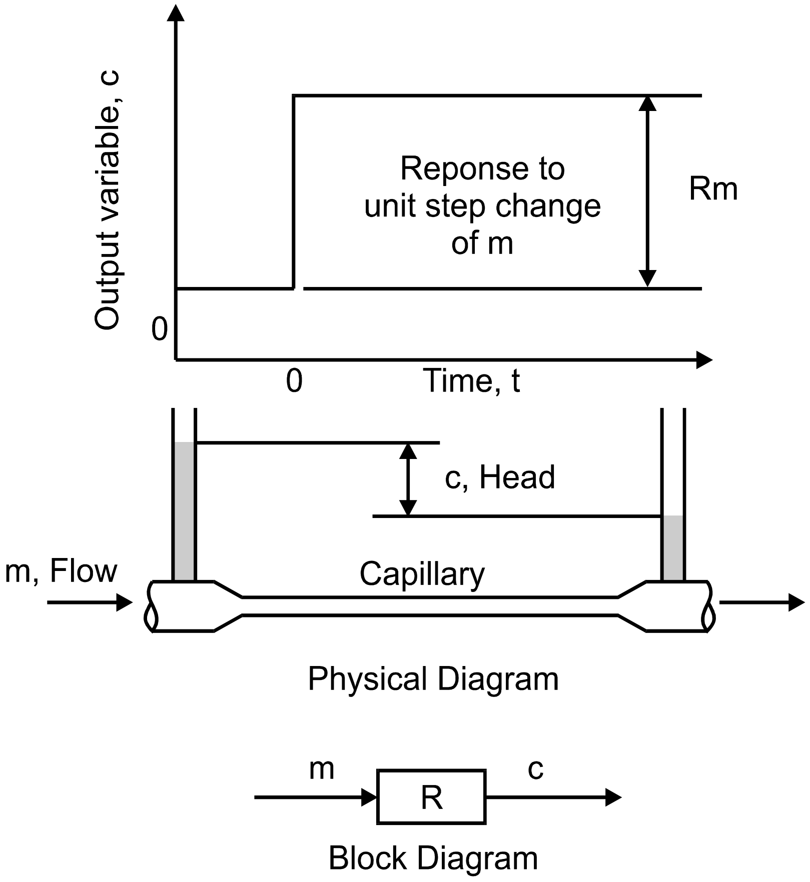
Transfer functions are used as a tool for analysis of a control system. Each element or block of the control system has its own characteristic transfer function. Using individual transfer functions representing individual system elements can be combined, using algebraic methods to represent the overall control system.

1.2 Process dynamics

In order to match a controller to a process it is necessary to understand the process dynamic characteristics. The majority of processes can be described in terms of resistance, capacitance and dead-time elements, which determines the dynamic and steady state responses of the process to disturbances.

Resistance type processes

The most obvious illustration of a resistance type process is the pressure drop through pipes and other equipment, i.e. where there is some resistance to the transfer of energy or mass. These parts of the process are known as 'resistances'.



$$c = Rm$$

where c = output resistance (head)
R = resistance
m = input variable (flow)

Figure 1.2
A capillary flow system illustrating the resistance (proportional) element

Figure 1.2 illustrates the operation of a capillary flow system where the flow is linearly proportional to the pressure drop. This process is described by a steady state gain, equal to the resistance (R). As the input (flow = m) changes instantaneously from zero to m, the output (head = c) undergoes an instantaneous change from zero to c = R x m.

This laminar resistance to flow is analogous to the electrical resistance (R) to current (i) flow as given by the Ohm's law, v = i x R.

In laminar flow, such as capillary flow, the resistance is a function of the square root of the pressure drop.

Flow processes usually consist of a flow measuring device and a control valve in series, with the flow (c) passing through both of them as shown in Figure 1.3.

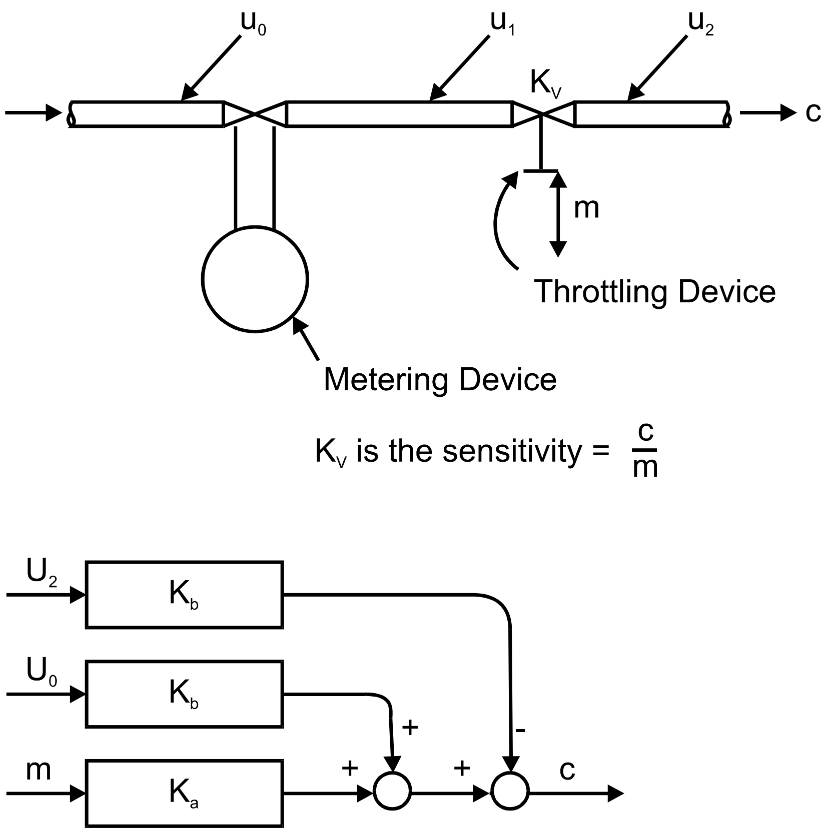


Figure 1.3
Flow is a resistance (proportional) process

The block diagram illustrates that this is an algebraic and proportional (resistive) process. The manipulated variable (m) is the operation of the control valve, and (c) is the controlled variable; this being the flow through the system. A change in (m) results in an immediate and proportional change in (c).

The amount of change is a function of process gain or sensitivity K_a. Load variables are U_0 and U_2 the up and down stream pressures and any change of these results in an immediate and proportional change in the flow (c). The amount of change is proportional to their process sensitivity (K_B).

The overall process equation is

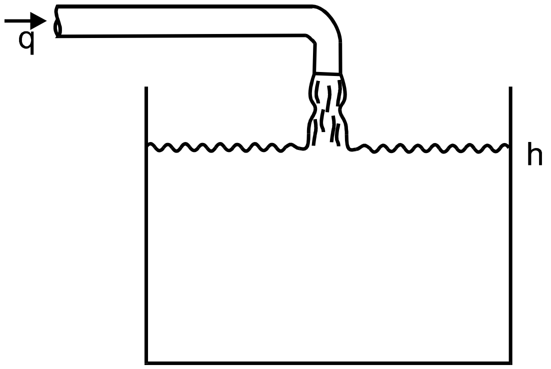
$$c = (K_a)m + (K_b)U_O - (K_b)U_2+M_3$$

Capacitance type processes

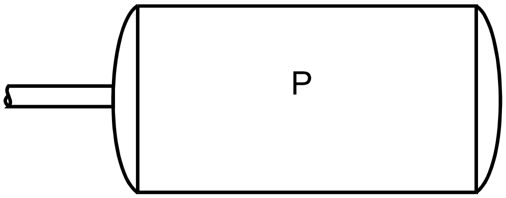
Most of the processes include some form of capacitance or storage capability, either for materials (gas, liquid, or solids) or for energy (thermal, chemical, etc.). Those parts of the process with the ability to store mass or energy are termed 'capacities'. Thermal capacitance is directly analogous to electrical capacitance, which is defined by Faraday's law.

The capacitance of a liquid or gas storage tank is expressed in area units. These processes are illustrated in Figure 1.4. The gas capacitance of a tank is constant and is analogous to electrical capacitance.

The liquid capacitance equals the cross-sectional area of the tank at the liquid surface; if this is constant then the capacitance is also constant at any head.



Liquid capacitance is defined by $C = \frac{dv}{dh}$ ft^2

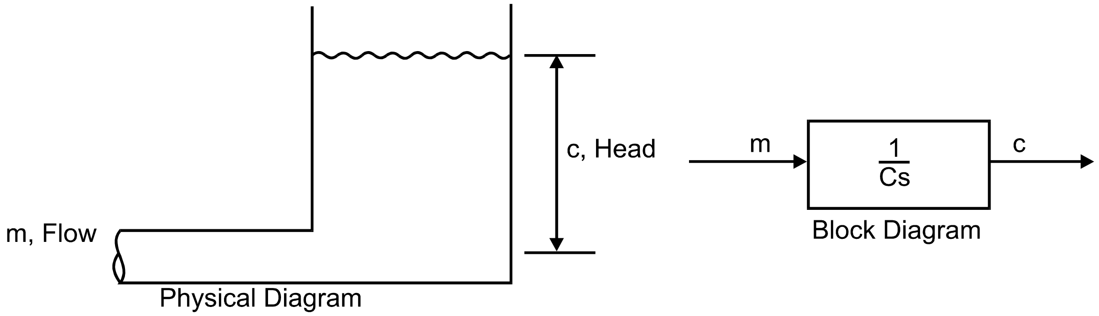


C, Capacitance

Gas capacitance is defined by
$C = \frac{dv}{dp} = \frac{V}{nRT}$ ft^2

where v = weight of gas in vessel, lb.
V = volume of vessel, ft^3
R = Gas constant of a specific gas ft/deg
p = pressure, lb.ft^2
n = polytropic exponent is between
1.0 and 1 .2 for uninsulated tanks

Figure 1.4
Capacitance of a liquid or gas storage tank expressed in area units



$$C\frac{dc}{dt} = m \quad = (Cs)c = m \therefore c = \left(\frac{1}{Cs}\right)m$$

where C = capacitance
c = output variable (head)
t = time
m = input variable (flow)
$s = \frac{d}{dt}$ = differential operator

Figure 1.5
Liquid capacitance calculation; the capacitance element

A purely capacitive process element can be illustrated by a tank with only an inflow connection such as Figure 1.5. In such a process, the rate at which the level rises is inversely proportional to the capacitance and the tank will eventually flood. For an initially empty tank with constant inflow, level c is the product of the inflow rate m and the time period of charging t divided by the capacitance of tank C.

Inertia Type Processes

Inertia effects are due to the motion of matter. They are most commonly associated with mechanical systems involving moving components, but are also important in some flow systems in which fluids must be accelerated or decelerated.

Resistance and capacitance are perhaps the most important effects in industrial processes involving heat transfer, mass transfer and fluid flow operations. The combined effect of supplying a capacity through a resistance is a time retardation. This is basic to most dynamic systems found in industrial processes.

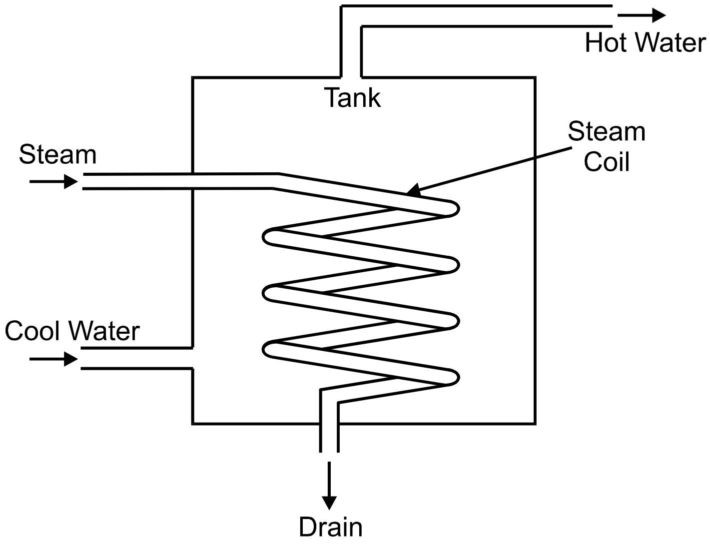


Figure 1.6
Resistance and capacitance effects in a water heater

As a result of this time retardation, an instantaneous change in the input to the system will not result in an instantaneous change in the output. Rather, the response will be slow, requiring a finite period of time to attain a new equilibrium.

1.3 Process time constants

Combining a capacitance type process element, such as a tank, and a resistance type process element, such as a valve, results in a single time constant process. In a mathematical sense, the time constant is the future time necessary to experience 63.2% of the change remaining to occur, at any moment in the process.

The time constant is a measure of the rapidity of the response of the process. It can be characterized in terms of the capacitance and resistance (or conductance) of the process.

First order response

In the basic case of a first order response, the maximum rate of change of output occurs immediately after a step change in input. 63.2% of the total response is attained after one time constant. If the system continued to change at its initial speed of response, the maximum response rate, it would reach 100% of the output change in one time constant. A physical example of a first order process is an initially empty tank with a constant inflow and a valve controlled outflow.

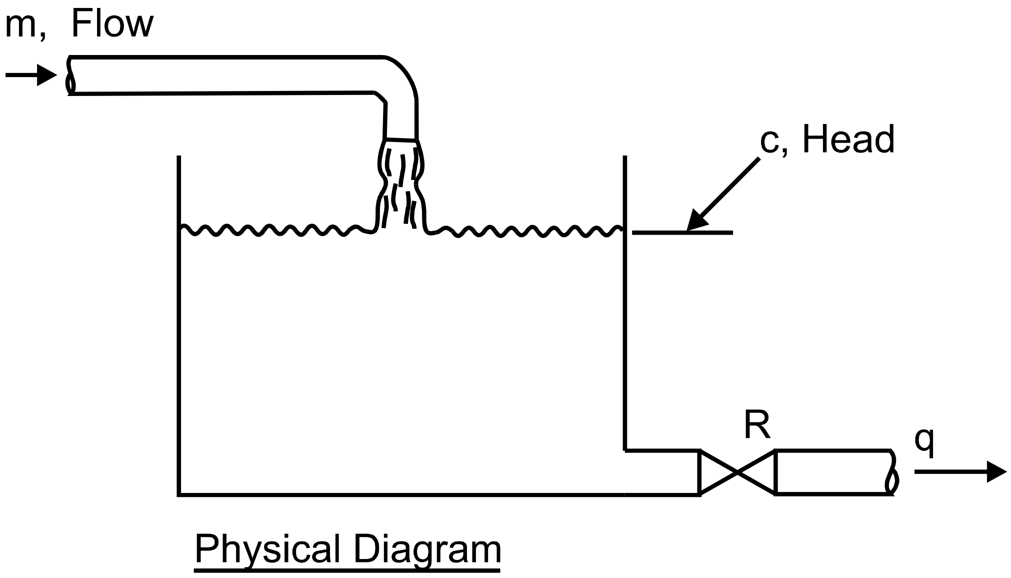


Figure 1.7
A physical example of a first order process: a constant inflow and a valve controlled outflow

The general equation for such a process is a linear first order differential equation:

$$T\frac{dc(t)}{dt} + c(t) = Km(t)$$

Where:

T	- Time constant of the process
K	- Gain of the process
t	- Time
c(t)	- process output response
m(t)	- process input response

Process elements of this description are common and are generally referred to as 'first order lags'. They may also be called 'linear lags' or 'exponential transfer lags'. Components with this response are characterized by the capacity to store material or energy and the dynamic shape of the response curve is described by a time constant.

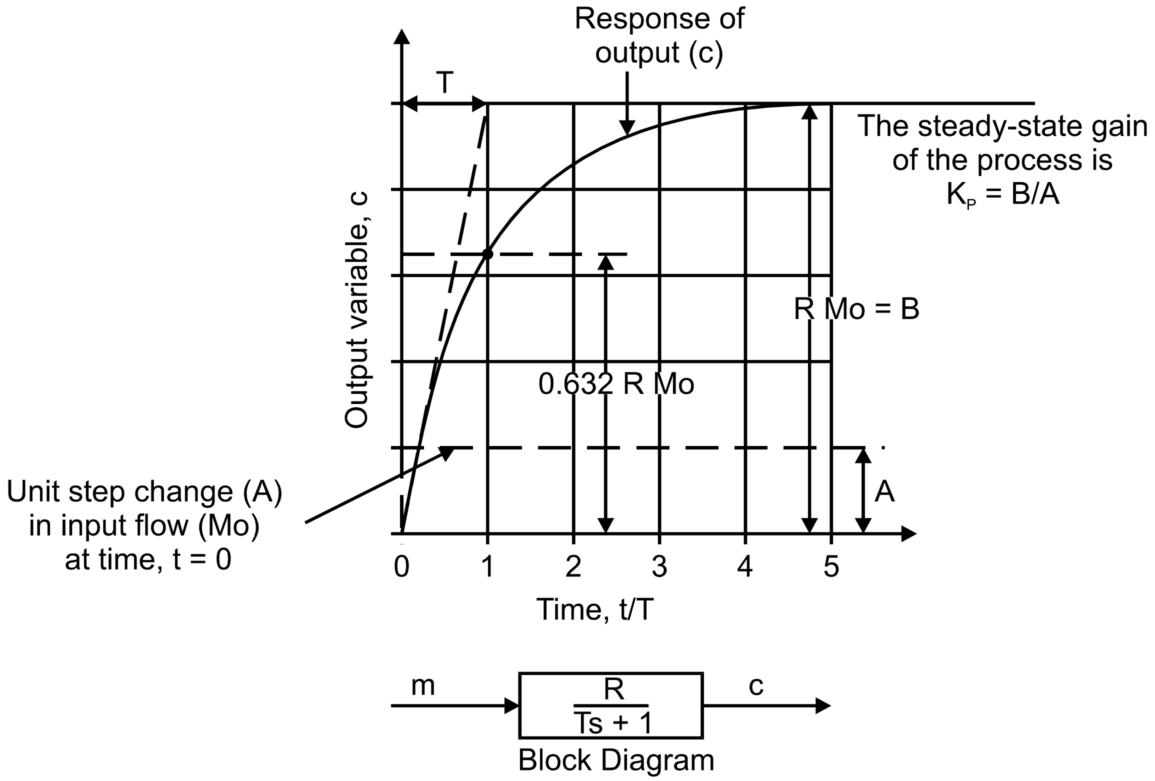


Figure 1.8
First order response

Exercise 1: Part 1.
For a practical demonstration of 1st order lag and the measurement of time constants we suggest that you now carry out IDC Practical Exercise no 1, part 1 using the PC-ControLAB simulation software tools that are available for this workshop

In multiple time constant processes, say where two tanks are connected in series, the system therefore has two time constants operating in series. As the number of time constants increases, the response curves of the system become progressively more retarded and the overall response gradually changes into an S-shaped reaction curve. This curve is typical of the majority of processes.

Second order response

Second order processes result in a more complicated response curve. This is due to inertia effects and interactions between first order resistance and capacitance elements. They are described by the second order differential equation:

$$\frac{d^2}{dt^2} c(t) + 2xw_n \frac{d}{dt} c(t) + w_n^2 c(t) = Kw_n^2 r(t)$$

Where,
w_n - natural frequency of the system
x - Damping ratio of the system
K - System gain
t - Time
$r(t)$ - input response of the system
$c(t)$ - output response of the system

The solutions to the equation for a step change in r(t) with all initial conditions zero can be any one of a family of curves shown in Figure 1.9. There are three possible cases in the solution, depending on the value of the damping ratio:

$x < 1.0$, the system is underdamped and overshoots the steady-state value.

If $x < 0.707$, the system will oscillate about the final steady-state value.

$x > 1.0$, the system is overdamped and will not oscillate or overshoot the final steady-state value.

$x = 1.0$, the system is critically damped. In this state it yields the fastest response without overshoot or oscillation.

The natural frequency term w_n is related to the speed of the response for a particular value of x. It is defined in terms of the 'perfect' or 'frictionless' situation where $x = 0.0$.

A large frequency tends to squeeze the response and a small frequency to stretch it.

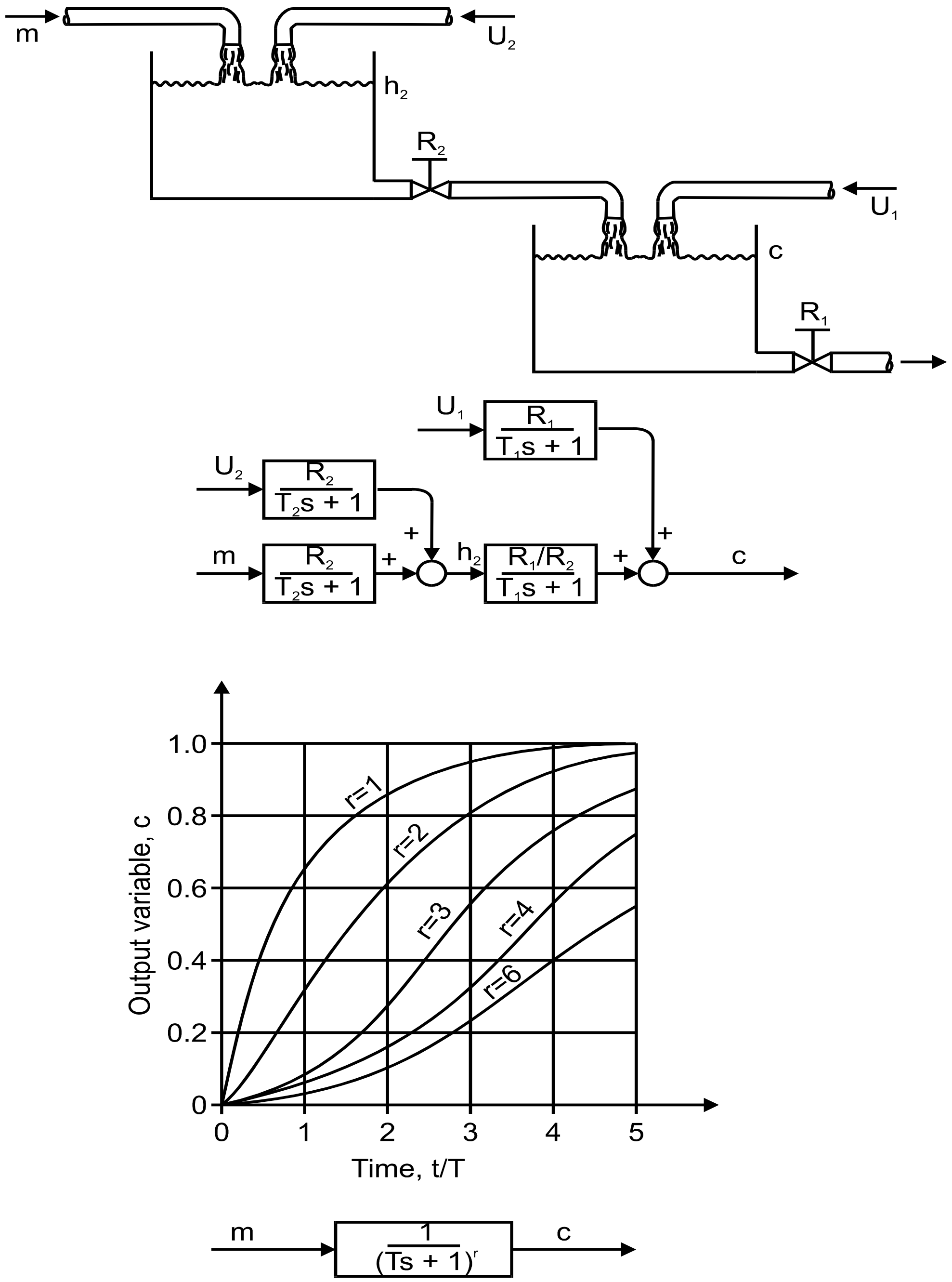


Figure 1.9
Second order response: two time constants in series, and response curves of processes with several time constants

High Order Response

Time delays can be used to approximate high-order model dynamics. Any process that consists of a large number of process units connected in series can be represented by a high order response. This transfer function could represent a series of first order transfer functions. In practice, the mathematical analysis of uncontrolled processes containing time delays is relatively simple but a time delay or a set of time delays, within a feedback loop tends to lend itself to very complex mathematics.

In general, the presence of time delays in control systems reduces the effectiveness of the controller. In well-designed systems the time delays (deadtimes) should be kept to the minimum.

1.4 Basic definitions and terms used in process control

As we will see in the later chapters, two of the most important signals used in process control are called

PROCESS VARIABLE or PV.

and the

MANIPULATED VARIABLE or MV.

In industrial process control, the PROCESS VARIABLE or PV is measured by an instrument in the field and acts as an input to a controller, which takes action based on the value of it. Alternatively the PV can be an input to computer based hardware system and its value displayed in some manner so that the operator can perform manual control and supervision.

The variable to be manipulated, in order to have control over the PV, is called the MANIPULATED VARIABLE or MV. If we control a particular flow for instance, we manipulate a valve to control the flow. Here, the valve position is called the MANIPULATED VARIABLE and the measured flow becomes the PROCESS VARIABLE.

In the case of a simple automatic controller, the Controller OUTPUT Signal (OP) drives the Manipulated Variable. In more complex automatic control systems, a controller output signal may not always drive a Manipulated Variable in the field. In practice, the term Manipulated Variable is rarely used. Most people involved in process control refer to the OP (output) of a controller and it is assumed that one knows the purpose of it.

The ideal value of the PV is often called TARGET VALUE. In the case of an automatic control, the term SET POINT VALUE is preferred.

1.5 Types or modes of operation of available control systems

There are five basic forms of control available in Process Control. These are:

- On-Off
- Modulating
- Open Loop
- Feed Forward
- Closed loop

On-Off control

The most basic control concept is the On-Off control, as found in a household iron. This is a very crude form of control, which nevertheless should be considered as a cheap and effective means of control if a fairly large fluctuation of the PV (process variable) is acceptable.

The wear and tear of the controlling element (such as actuator, solenoid valve etc) needs special consideration. As the bandwidth of fluctuation of a PV is increased, the frequency of switching (and thus wear and tear) of the controlling element decreases.

Modulating control

If the output of a controller can move through a range of values, we have modulating control. It is understood that modulating control takes place within a defined operating range (with an upper and lower limit) only.

Modulating control can be used in both open and closed loop control systems.

Open loop control

We have open loop control if the control action (controller output signal OP) is not a function of the PV (process variable) or load changes. The open loop control does not self-correct when the PVs drift.

Feed forward control

Very often it is a form of control based on measured disturbances (feed forward control). It is a form of open loop control, as the PV is not used in the control action.

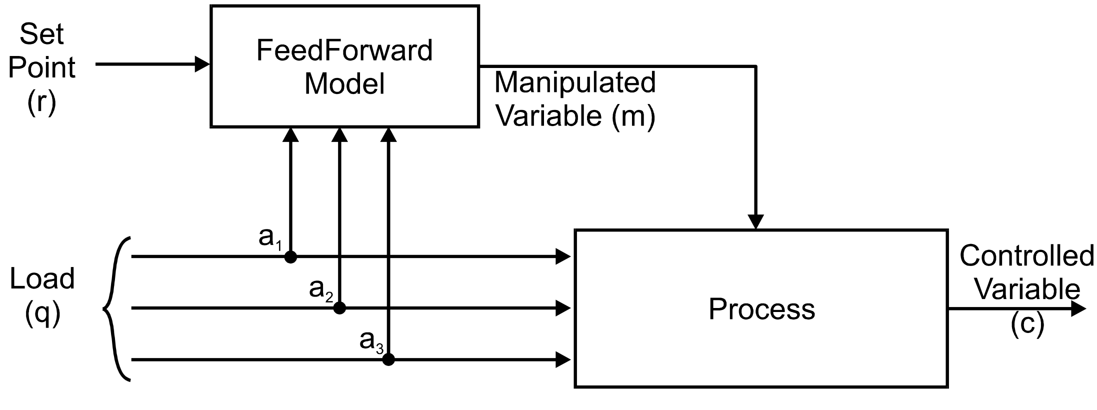


Figure 1.10
The feedforward control loop

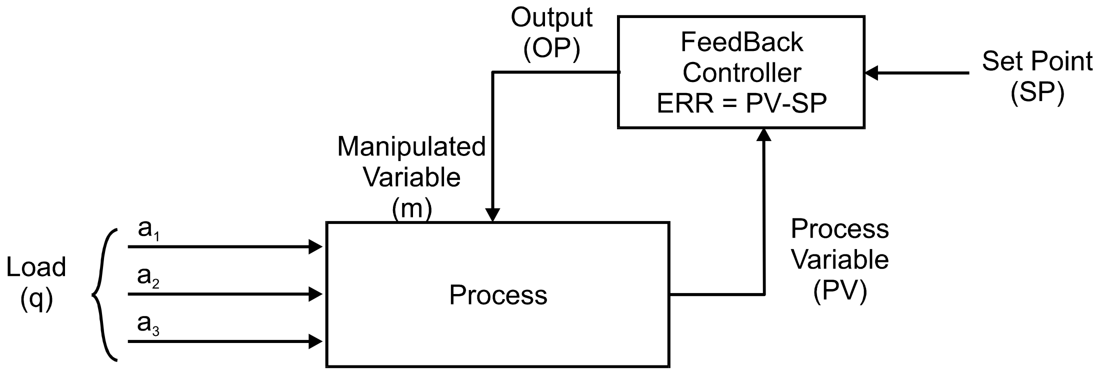
Feedforward is a more direct form of control than finding the correct value of the manipulated variable (MV) by trial and error as occurs in feedback control. In feedforward the major process variables are fed into a model to calculate the manipulated variable (MV) required to control at setpoint (SP).

Figure 1.10 shows a block diagram of a feedforward control loop. The PV (controlled variable c) is a result of the control action.

In practice, feedforward control is used in combination with feedback or closed loop control. In hybrid feedforward control, the imperfect feedforward control corrects up to 90% of the upsets, leaving the feedback system to correct the 10% bias left by the feedforward component.

Closed loop or feedback control

We have a closed loop control system if the PV, the objective of control, is used to determine the control action. The principle is shown in Figure 1.11.



$$OP = (m) = K_C \left(E_{RR} + \frac{1}{T_{int}} \int E_{RR}\, dt + T_{der} \frac{d}{dt} E_{RR} \right) + \text{Manual}$$

Figure 1.11
The feedback control loop

The idea of closed loop control is to measure the PV (process variable). Compare this with the SP (setpoint), which is the desired or target value; and determine a control action that results in a change of the OP (output) value of an automatic controller.

In most cases, the ERROR (ERR) term is used to calculate the OP value.

ERR = PV - SP

If ERR = SP -PV has to be used, the controller has to be set for REVERSE control action.

1.6 Closed loop controller and process gain calculations

Within this closed loop form of control there are two functional gain blocks, one being in the controller and the other in the process being controlled. The LOOPGAIN (K_{LOOP}) is the product of the CONTROLLER GAIN (K_C) and the PROCESS GAIN (K_P).

$$\text{LOOPGAIN } (K_{LOOP}) = K_C \times K_P = \frac{\Delta MV}{\Delta E} X \frac{\Delta PV}{\Delta MV} = \frac{\Delta PV}{\Delta E}$$

Where:

$$\text{Process gain } (K_P) = \frac{\Delta PV}{\Delta MV}$$

and

$$\text{Controller gain } (K_C) = \frac{\Delta MV}{\Delta E}$$

As the total constituent parts of the entire loop consist of a minimum of 4 functional items; the process gain $(K_P) = \frac{\Delta PV}{\Delta MV}$

Controller gain $(K_C) = \frac{\Delta MV}{\Delta E}$

the measuring transducer or sensor gain, K_S and finally the valve gain K_V. The total loop gain is the product of these four operational blocks.

For ¼ damping, the ideal response where each oscillation has a ¼ of the amplitude of the previous cycle then:

$$\text{KLOOP} = (K_C \times K_P) = \left(\frac{\Delta MV}{\Delta E} X \frac{\Delta PV}{\Delta MV} = \frac{\Delta PV}{\Delta E}\right) \text{ x } K_S \text{ x } K_V = 0.5$$

1.7 Proportional, integral and derivative control modes

Most closed loop controllers are capable of controlling with three control modes that can be used separately or together

- Proportional control (P)
- Integral, or reset control (I)
- Derivative, or rate control (D)

The purpose of each of these control modes is as follows:

Proportional control...

This is the main and principal method of control. It calculates a control action proportional to the ERROR (ERR). Proportional control cannot eliminate the ERROR completely.

Integral control ... (reset)

This is the means to eliminate completely the remaining ERROR or OFFSET value, left from the proportional action. This may result in reduced stability in the control action.

Derivative control ... (rate)

This is sometimes added to introduce dynamic stability to the control LOOP.

Note:

The terms ***RESET*** for integral and ***RATE*** for derivative control actions are seldom used nowadays.

Derivative control has no functionality on its own.

The only combinations of the P, I and D modes are:

P	For use as a basic controller
PI	Where the offset caused by the P mode is removed
PID	To remove instability problems that can occur in PI mode
PD	Used in cascade control; a special application
I	Used in the primary controller of cascaded systems

1.8 An introduction to cascade control

Controllers are said to be "in cascade" when the output of the first or primary controller is used to manipulate the setpoint of another or secondary controller. When two or more controllers are cascaded, each will have its own measurement input or PV but only the primary controller can have an independent setpoint (SP) and only the secondary, or the most down-stream controller has an output to the process.

Cascade control is of great value where high performance is mandatory in the face of random disturbances, or where the secondary part of a process contains an undue amount of phase shift. Cascade control is one of the successful methods for improving the control performance and reducing the maximum deviation and integral error for disturbance responses. Cascade control has been used widely, as it is easy to implement and requires simple calculations.

The principal advantages of cascade control are:

- The secondary controller corrects disturbances occurring in the secondary loop before they can affect the primary, or main, variable.
- The secondary controller can significantly reduce phase lag in the secondary loop thereby improving the speed or response of the primary loop.
- Gain variations in the secondary loop are corrected within that loop.
- The secondary loop enables exact manipulation of the flow of mass or energy by the primary controller.

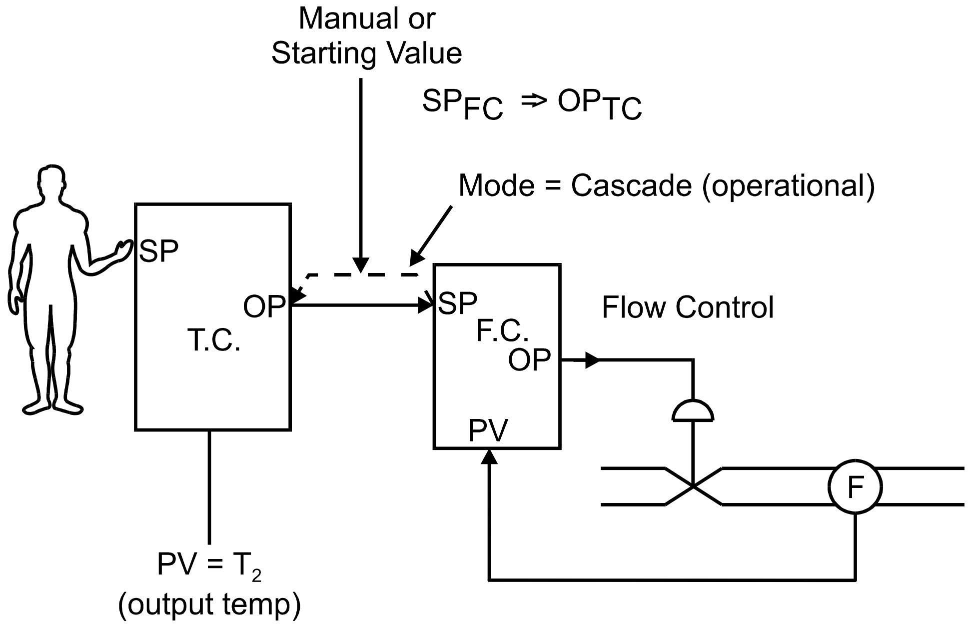


Figure 1.12
An example of cascade control

An example of cascade control is shown in Figure 1.12. The primary controller, TC, is used to measure the output temperature, T_2, and compare this with the setpoint value of the TC. The secondary controller, FC, is used to keep the fuel flow constant against variables like pressure changes.

The primary controller's output is used to manipulate the SP of the secondary controller thereby changing the fuel feed rate to compensate for temperature variations of T_2 only. Variations and inconsistencies in the fuel flow rate are corrected solely by the secondary controller: the FC controller.