وزارة  البحث العلمي والتعليم العالي

MINISTERE DE L'ENSEIGNEMENT SUPEREUR ET DE LA RECHERCHE SCIENTIFIQUE

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Faculté des Sciences et de la Technologie

DEPARTEMENT DE GENIE DES PROCEDES


**N° d'ordre : M2 /GC/2022**

# MEMOIRE DE FIN D'ETUDES
# MASTER ACADEMIQUE

**Filière :** Génie des procédés **Option:** Génie Chimique

# Thème

## IMPLEMENTATION OF OPTIMIZATION TECHNIQUES WITH CONSTRAINTS

**Design and Operating Conditions of Heat Exchangers**

Présenté par :**MANGEZI  Jubilee Kudzalshe**

Soutenu le:   14/07/ 2022 devant le  jury composé de :

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Année Universitaire 2021/2022

# ACKNOWLEDGEMENTS

*I would like to acknowledge and give my warmest thanks to my supervisor Dr. Benmekki who made this work possible and very exciting. His guidance, immense knowledge, vast experience  and advice carried me through all the stages of writing my project and l am very grateful. Dr. Benmekki has inflamed my passion more and also deepen my understanding of  Chemical Engineering. I could not have imagined having a better advisor and mentor for my Masters study.*

*I would also like to give special thanks to Mr & Momz Ngwindi, Mr T. Nyamuda and Mr &  Mrs  Benza for their extraordinary continous support in everything from the very first day. The story of my life is meaningless without mentioning about you my bonafide family. Your  prayers, precious advise and tremendous support has sustained me this far and l am ever grateful. A special thanks also goes to my friends Team Fridge who became like a family to me in Algeria, they proved loyalty  in both good and bad times. A very special thanks also goes to my bond and loyal brother Truswell Munashe who played a special role in my life during my stay in this land to mold me in many aspects of life.*

*Finally, l want to thank my ever faithful Father God, for His mercy, favour, blessings and strength through all my journey towards destiny. I have experienced your guidance day by day. You are the reason for my being and without you I fall, without His Presence my world becomes gloom.  You are the one who let me finish my Master; forever I will keep on trusting you for my future. Better is not good enough but the best is yet to come.*

# ABSTRACT

The purpose of this study is to implement optimization techniques with constraints to the design and operating conditions of a heat exchanger.

We have developed a mathematical model governing heat exchange in a shell-tube heat exchanger which consists of two first order ordinary differential equations solved numerically.

We have implemented a subroutine from the International Mathematical and Statistical Library with the formulation of an objective function adapted to the design and operating conditions with constraints.

# Table of Contents

## INTRODUCTION

In Chemical Engineering we apply optimization techniques for the design and conception of different equipments. The purpose of optimization is to achieve the best design relative to a set of prioritized criteria or constraints.

In chemical processing units, optimization is the method that seeks to solve the problem of minimizing or maximizing an objective function that relates the variable to optimize with the design and operating variables. The criteria for analysis of the economic objective function involve fulfilling a process criteria restrictions, conditions, design equations and respecting the limits of the variables.

Most problems in chemical engineering processes have many solutions, in some cases becoming endless. The optimization is related to the selection of an option that is best in a variety of efficient options but being the only one that comes closest to an economic optimum performance and operation. The reason why engineers optimize is that they work to improve the initial design of equipment and strive to enhance the operation of that equipment once it is installed so as to realize the largest production, the greatest profit, the minimum cost, the least energy usage and so on.

In our case we are going to optimize with constraints in order to design a shell and tube heat exchanger model. Constraints control and are logical conditions that - a solution to an optimization problem must satisfy - reflect real world limits on production capacity, market demand and available funds.

Fortran is a general-purpose, compiled programming language that is especially suited to numeric computation and scientific computing. Fortran was originally developed by IBM in the 1950s for scientific and engineering applications, and subsequently came to dominate scientific computing.

Heat Exchangers are used to transfer heat from one medium to another. These media may be a gas, liquid, or a combination of both .The media may be separated by a solid wall to prevent mixing or may be in direct contact.

There exist many types of heat exchangers, each type having its own advantages and its own limitations. In this work we are interested in the shell and tube model of heat exchanger. The shell and tube type consists of parallel arrangement of tubes in a shell. One fluid flows through the tubes and the other fluid flows through the shell over the tubes. Tubes maybe arranged in the shell to allow for parallel flow, counter flow, cross flow or both.

# Chapter I

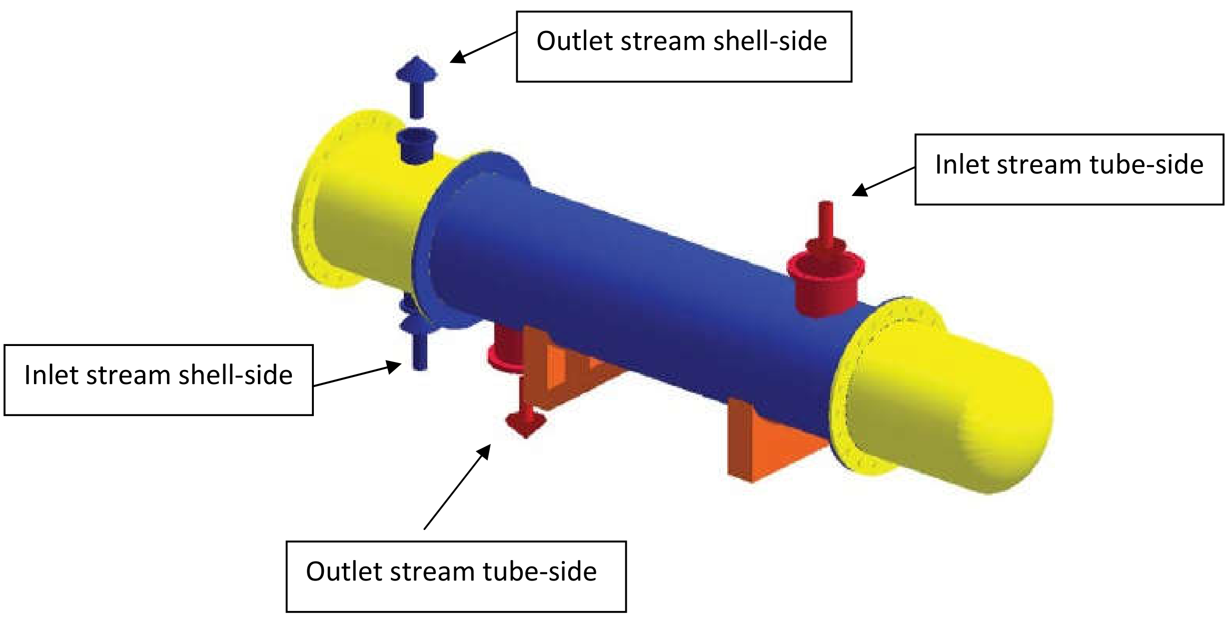
# SHELL AND TUBE HEAT EXCHANGER

## I.1.Function of the exchanger

A Shell and Tube heat exchanger is the most common type of heat exchangers in oil refineries and other large chemical processes, and is suited for higher pressure applications. As its name implies, this type of heat exchanger consists of a shell with a bundle of tubes inside it. One fluid runs through the tubes, and another fluid flows over the tubes -though the shell- to transfer heat between the two fluids.

The shell and tube heat exchanger (STHE) is a type of heat exchanging device constructed using a large cylindrical enclosure, or shell, that has bundles of tubing compacted in its interior. The use and popularity of shell and tube heat exchangers is due to the simplicity of their design and efficient heat rate.

## I.2. Diagram of the STHE



## I.3.Theory and Applications

Two fluids, of different starting temperatures, flow through the heat exchanger. One flows through the tube side and the other flows through the shell side. Heat is transferred from one fluid to the other through the walls, either from tube side to shell side or vice-versa. In order to transfer heat efficiently, a large heat transfer area should be used, leading to the use of many tubes.

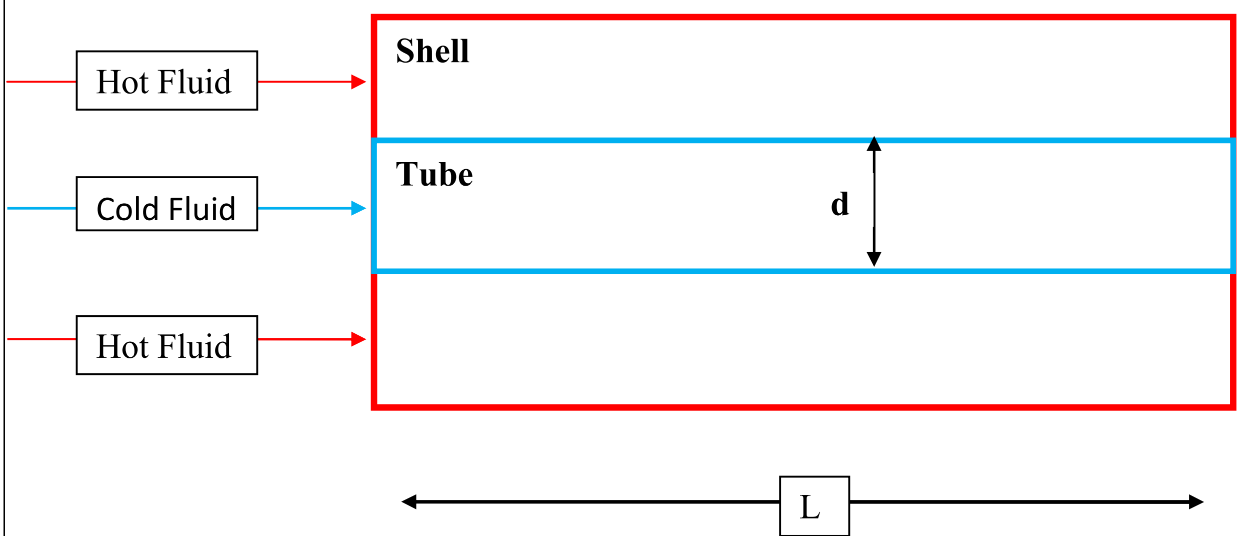
Heat exchangers with only one phase on each side can be called one-phase or single-phase heat exchangers. Two-phase heat exchangers can be used to heat a liquid to boil it into vapor, sometimes called boilers, or to cool the vapors and condense it into a liquid, called condensers, with the phase change usually occurring on the shell side, [1],[2].

They are also used in liquid-cooled chillers and in air-cooled chillers with a refrigerant.

# Chapter II

## MATHEMATICAL MODEL FOR SHELL AND TUBE HEAT EXCHANGER

### II.1.Tubular Heat Exchanger operating with parallel currents

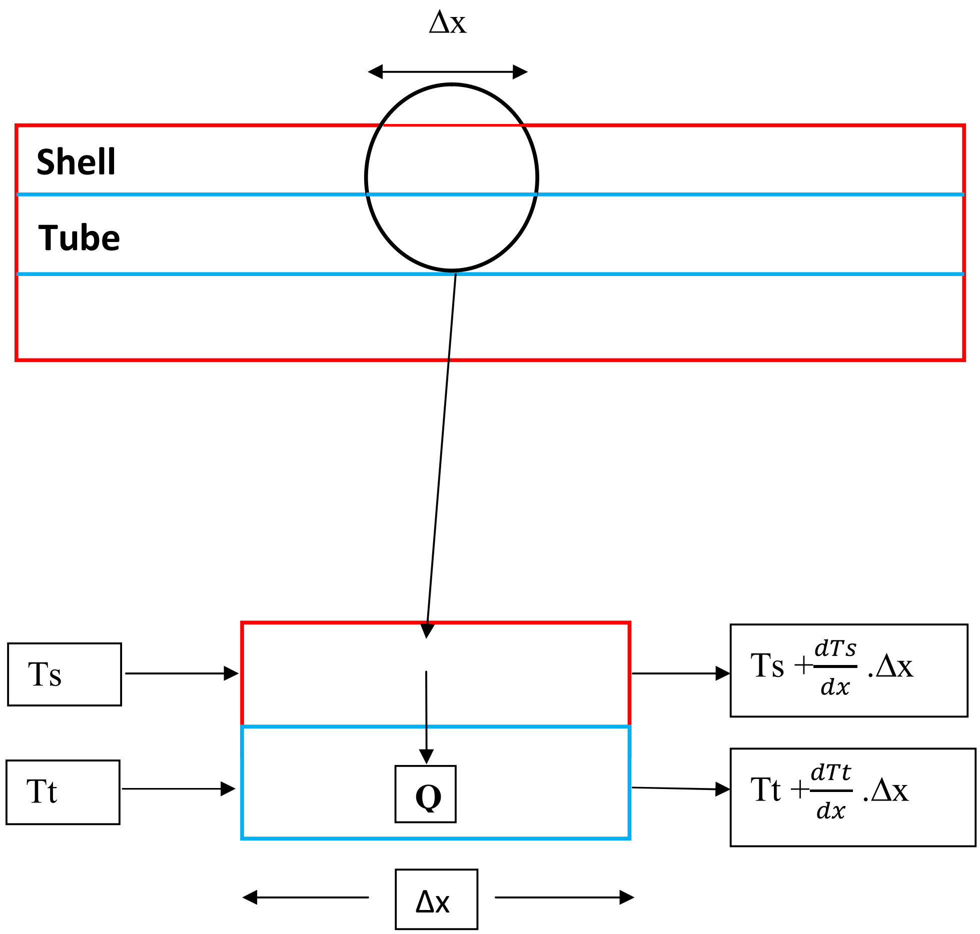



### II.2. Mathematical model governing the heat transfer

Nomenclature:

- Fs: flow rate of fluid in the shell
- Ft: flow rate of fluid in the tube
- Ts: temperature of the shell-side fluid
- Tt: temperature of the tube-side fluid
- Cs and Ct: heat capacities of shell-side and tube-side fluids, respectively
- U: overall heat transfer coefficient
- d: tube diameter
- L: length of the heat exchanger.

## HEAT BALANCE




Heat balance (Shell side): $Fs\ Cs\ Ts = Q + Fs\ Cs\ (Ts + \frac{dTs}{dx}\Delta x)$

$$\frac{dTs}{dx} = -Q / FsCs\Delta x \quad \text{Equation 1}$$

Heat balance (Tube side): $Ft\ Ct\ Tt + Q = Ft\ Ct\ (Tt + \frac{dTt}{dx}\Delta x)$

$$\frac{dTt}{dx} = Q / FtCt\Delta x \quad \text{Equation 2}$$

Quantity of Heat transferred : $Q = U.A.\Delta T = U.\pi.d.\Delta x\ (Ts - Tt)$

Equation 1 becomes: $\frac{dTs}{dx} = -U.\pi .d.(Ts - Tt)/ FsCs$ ($1^{st}$ differential equation)

Equation 2 becomes : $\frac{dTt}{dx} = U.\pi .d.(Ts - Tt)/ FtCt$ ($2^{nd}$ differential equation)

The mathematical model governing Heat transfer in a tubular exchanger consists of a system of two $1^{st}$ order differential equations.

# Chapter III

# NUMERICAL METHODS FOR SOLVING ORDINARY DIFFERENTIAL EQUATIONS

## III.1. Runge Kutta method

The most commonly method for solving ordinary differential equations (ODE) is the Runge Kutta formula of order 4 -RK-4- as it gives the best trade-off between computational requirements and accuracy.

## III.2. Algorithm of RK-4 method for a system of ODE

Solution of a system of 1st ODE or an equation of high order ODE which reduces to a system of 1st order, for example:

we have to solve $\frac{d^2y}{dx^2} + \frac{dy}{dx} - 6y = 0$ which is a 2nd order ODE

It will reduce to a system of two (2) differential equations of 1st order:

$\left\{\frac{dy}{dx} = z\right.$ and $\left\{\frac{dz}{dx} = 6y - z\right.$ with the initial values $y(0)$ and $z(0)$

we know that for a two general 1st order ODE's:

$\frac{dy}{dx} = f(x,y,z)$

$\frac{dz}{dx} = g(x,y,z)$

The RK-4 formula for a system of two ODE's are:

$y_{i+1} = y_i + \frac{1}{6}(k_0 + 2k_1 + 2k_2 + k_3)$

$z_{i+1} = z_i + \frac{1}{6}(l_0 + 2l_1 + 2l_2 + l_3)$

Where:

$k_0 = hf(x_i, y_i, z_i)$

$k_1 = hf(x_i + \frac{1}{2}h, y_i + \frac{1}{2}k_0, z_i + \frac{1}{2}l_0)$

$k_2$ =hf($x_i + \frac{1}{2}$h,$y_i + \frac{1}{2}k_1, z_i + \frac{1}{2}l_1$ )

$k_3 = hf(x_i +$ h,$y_i + k_2, z_i + l_2$ )

And :

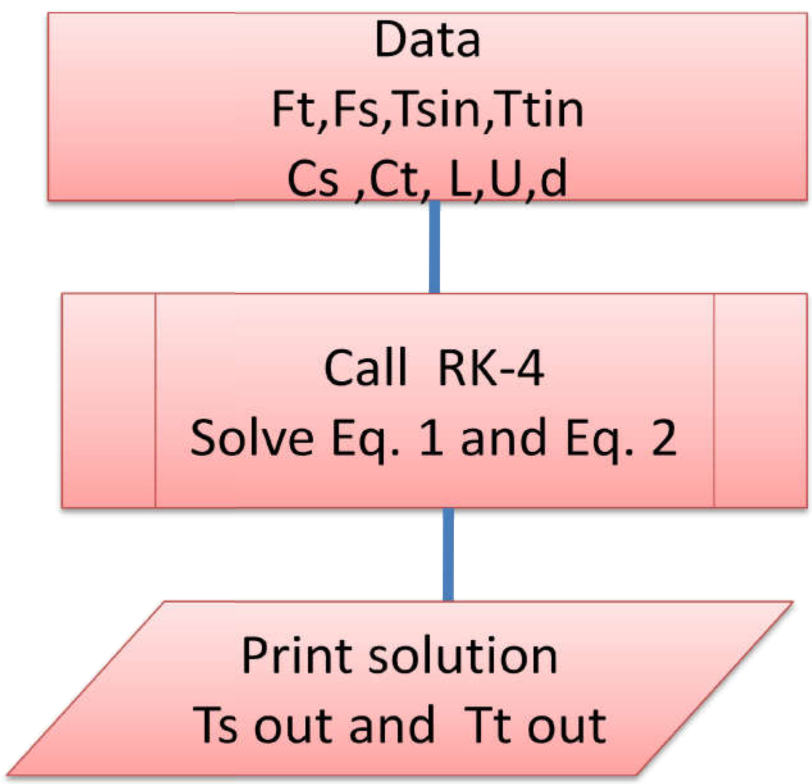
$l_0$ =hg($x_i, y_{i,}z_i$)

$l_1$ =hg($x_i + \frac{1}{2}$h,$y_i + \frac{1}{2}k_0, z_i + \frac{1}{2}l_0$ )

$l_2$ =hg($x_i + \frac{1}{2}$h,$y_i + \frac{1}{2}k_1, z_i + \frac{1}{2}l_1$ )

$l_3$ =hg($x_i +$ h,$y_i + k_2, z_i + l_2$ )

## III.3. Flow-chart for the solution of the mathematical model with RK-4



```fortran
C*******************************************************************************
C                        RESOLUTION OF THE MATHEMATICAL MODEL                  *
C                            RUNGE-KUTTA METHOD - ORDER 4                      *
C*******************************************************************************
C         used to find outlet temperatures from the tube and shell sides
C                                   Tsout and Ttout
C*******************************************************************************
C
      implicit double precision (a-h,o-z)
      double precision k(2,4)
c
c ------------------------------------------------------------------------------
c                       INPUT DATA
c tso: inlet temperaure of the hot fluid in shell side (units)
c tto: inlet tempeaure of the cold fluid in tube side (units)
c u   : heat transfert coefficient (units)
c cs : heat capaciy hot fluid
c ct : heat capaciy cold fluid
c fs : flow rate hot fluid
c ft : flow rate cold fluid
c -------------------------------------------------------------------------------

      data u,fs,ft,cs,ct/1250.0d0,106.0d0,71.0d0,1.0d0,1.0d0/

      f1(ts,tt) = -(3.14*u*d*(ts-tt))/(fs*cs)
      f2(ts,tt) =  (3.14*u*d*(ts-tt))/(ft*ct)
 1    x0=0.00d0
c
      print*,'enter inlet HOT TEMPERATURE='
      read*,ts0
      print*,'enter inlet COLD TEMERATURE='
      read*,tt0
      print *,' enter DIAMETER= '
      read *,d
c
      print *,'enter length L = '
      read *,xmax
      print *,' enter dtep size h = '
      read *,h
      n=idnint((xmax-x0)/h)
      do 10 i=1,n
        k(1,1) =h*f1(ts0,tt0)
        k(2,1) =h*f2(ts0,tt0)
c
        k(1,2)=h*f1(ts0+k(1,1)/2.,tt0+k(2,1)/2.)
        k(2,2)=h*f2(ts0+k(1,1)/2.,tt0+k(2,1)/2.)
c
        k(1,3)=h*f1(ts0+k(1,2)/2.,tt0+k(2,2)/2.)
        k(2,3)=h*f2(ts0+k(1,2)/2.,tt0+k(2,2)/2.)
c
        k(1,4)=h*f1(ts0+k(1,3),tt0+k(2,3))
        k(2,4)=h*f2(ts0+k(1,3),tt0+k(2,3))
c
        ts1= ts0 + (k(1,1)+2.0d0*k(1,2)+2.0d0*k(1,3)+k(1,4))/6.0d0
        tt1= tt0 + (k(2,1)+2.0d0*k(2,2)+2.0d0*k(2,3)+k(2,4))/6.0d0
c
        xb=x0+dfloat(i)*h
        ts0= ts1
        tt0= tt1
10    continue
      write(*,600)xb,ts1,tt1
600   format(10x,'x=',d10.3,3x,'ts=',d25.15,/,25x,'tt=',d25.15)
      print *,'ENTRER: "1"  POUR CONTINUER'
      print *,'        "0"  POUR QUITTER LE PROGRAMME'
      print *,'             '
      read *,iflag
      if(iflag.eq.1)goto 1
      stop
      end
```

# Chapter IV

# OPTIMIZATION/MINIMIZATION TECHNIQUES

## IV.1. Minimization of a function of N-variables without constraint - Gradient method

A gradient method is a generic and simple optimization approach that iteratively updates the parameters to go up (down in the case of minimization) [3],[4].

Min f(x), x $\in R^n$

With the search directions defined by the gradient of the function at the current point.

$$\left.\begin{aligned} \bar{x}^{k+1} &= \bar{x}^k + \lambda\Delta\bar{x} \\ \Delta\bar{x} &= -\nabla f(\bar{x}) \end{aligned}\right\} \quad \boldsymbol{\bar{x}^{k+1} = \bar{x}^k - \lambda\nabla f(\bar{x})} \qquad \text{with } \bar{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$$

The step size $\lambda$ is found such that $f(\bar{x}^{k+1})$ is minimum.

$$\frac{\partial f(\bar{x}^{k+1})}{\partial \lambda} = 0$$

The direction is given by:

$$\nabla f(\bar{x}) = \begin{bmatrix} g_1 = \dfrac{\partial f(\bar{x})}{\partial x_1} \\ g_2 = \dfrac{\partial f(\bar{x})}{\partial x_2} \\ \vdots \\ g_n = \dfrac{\partial f(\bar{x})}{\partial x_n} \end{bmatrix}$$

Stopping criterion:

$$\|\nabla f(\bar{x})\| < \varepsilon \ (tolerance)$$

$$\|\nabla f(\bar{x})\| = \sqrt{{g_1}^2 + {g_2}^2 + \cdots {g_n}^2}$$

## IV.2. Minimization of a function of N-variables with constraints – IMSL library

The **I**nternational **M**athematical and **S**tatistical **L**ibrary -**IMSL**- is a collection of software libraries of numerical analysis functionality that are implemented in the computer programming languages like C and Fortran. The library consists of two separate but coordinated libraries that allow easy user access.

These libraries are organized as follows:

- Math/Library: general applied mathematics and special functions.
- Stat/Library: statistics.

Most of the routines are available in both single and double precision versions. Each routine is designed and documented to be used in research activities as well as by technical specialists.

To use any of these routines, you must write a program in Fortran or possibly some other language to call the Math/Library routines.

### IV.2.1. Subroutine BCONF

In our case we are going to use and apply BCONF subroutine from the IMSL. We have BCONF for single precision and DBCONF for double precision. We use BCONF to minimize a function of N-variables subject to bounds -lower bounds and upper bounds- on the variables using a quasi-Newton method and a finite difference gradient.

It uses an active set strategy to solve minimization problems subject to simple bounds on the variables. The problem is stated as follows:

$$\min f(x) \quad x \in R^n$$

$$\text{subject to } \; I \leq x \leq u$$

From a given starting point $x^c$, an active set IA , which contains the indices of the variables at their bounds, is built. A variable is called a “free variable”, if it is not in the active set. The routine then computes the search direction for the free variables according to the formula:

$$d = -B^{-1} g^c$$

where B is a positive definite approximation of the Hessian and $g^c$ is the gradient evaluated at $x^c$; both are computed with respect to the free variables. The search direction for the variables in IA is set to zero. A line search is used to find a new point $x^n$,

$$x^n = x^c + \lambda d\,, \qquad \lambda \in (0, 1]$$

such that :

$$f(x^n) \leq f(x^c) + \alpha g^T d, \qquad \alpha \in (0, 0.5)$$

Finally, the optimality conditions :

$$\| g(x_i) \| \leq \varepsilon \qquad , l_i < x_i < u_i$$

$$g(x_i) < 0 \qquad , \ x_i = u_i$$

$$g(x_i) > 0 \qquad , \ x_i = l_i$$

are checked, where $\varepsilon$ is a gradient tolerance. When optimality is not checked, B is updated according to the BFGS formula :

$$B \leftarrow B - \frac{B_{ss}{}^T B}{S^T B_s} + \frac{y y^T}{y^T s}$$

where $s = x^n - x^c$ and $y = g^n - g^c$ . Another search direction is then computed to begin the next iteration.

The active set is changed only where a free variable hits bounds during an iteration or the optimality condition is not for the free variables but not for all variables, in IA, the active set. In the latter case, a variable that violates the optimality condition will be dropped out of IA. Since a finite difference method is used to estimate the gradient for some single precision calculations, an inaccurate estimate of the gradient may cause the algorithm to terminate at a non critical point.

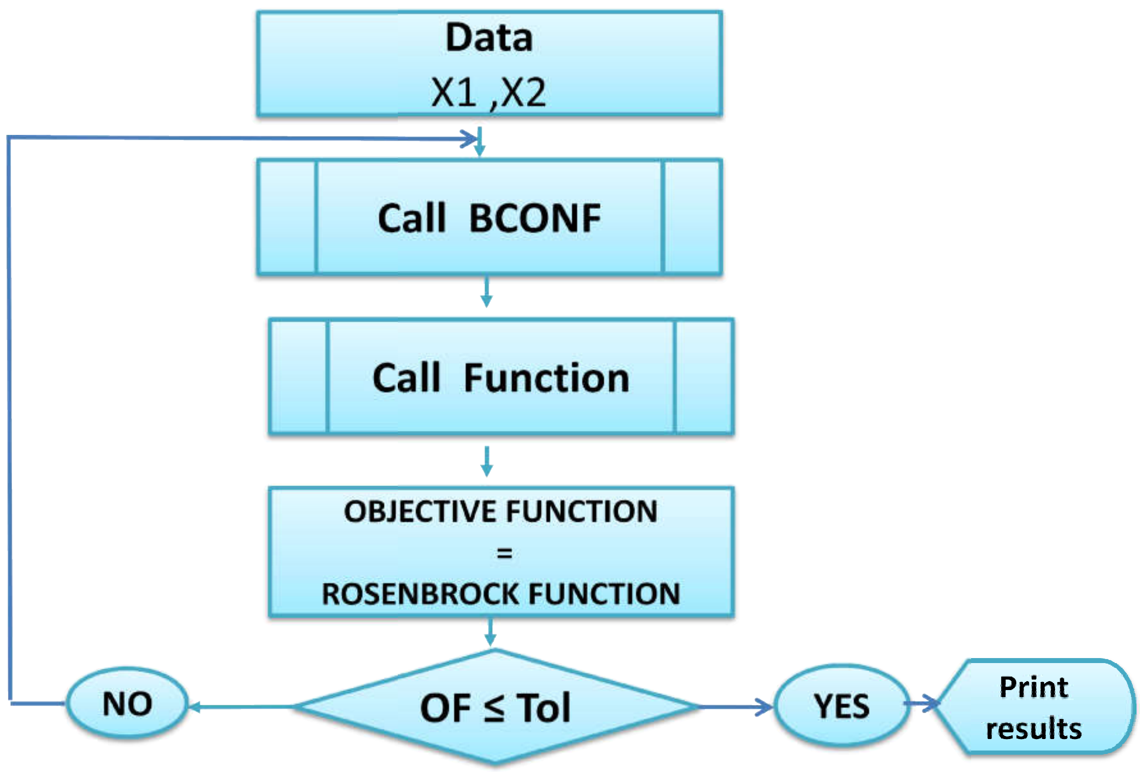
## IV.2.2. Algorithm for an analytical function with the BCONF subroutine

The Rosenbrock function, also referred to as the Valley or Banana function, is a popular test problem for gradient-based optimization algorithms. The function is unimodal and the global minimum lies in a narrow, parabolic valley. We can use the Rosenbrock function with constraints from the data in the International Mathematics and Statistics Library,

The Rosenbrock Function:

f $(x_{1,}x_2)$ =100$(x_2 - x_1{}^2)^2$ +$(1 - x_1)^2$

is used to find solutions of $x_1$ *and* $x_2$ in order to minimize the function with bounds -upper bounds and lower bounds



## IV.3. Applying BCONF to the design and operating conditions of Heat Exchanger

First of all we have to formulate the objective function either for calculating some operating conditions or for the design, calculating for example the diameter of the tubes and the length of the heat exchanger.

The objective function for the heat exchanger is formulated as follows:

$$\mathbf{OF} = \left| \boldsymbol{T}_{wanted\ value} - \boldsymbol{T}_{calculated} \right|$$

***T:*** outlet temperatures which can be the outlet temperature from the shell side (defined as Tsout) or the outlet temperature from the tube side (defined asTtout).

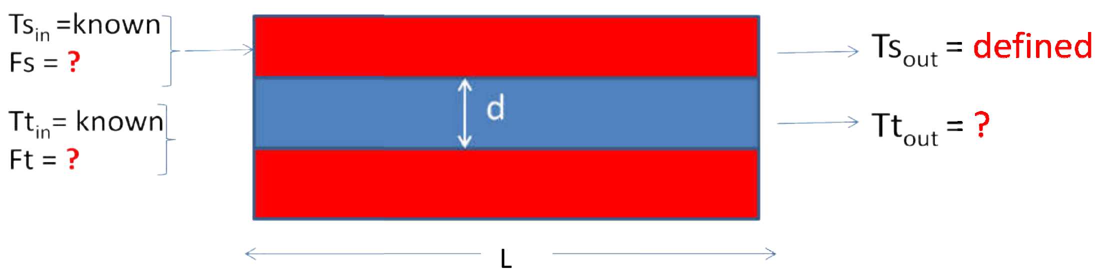
***T***(calculated) is obtained by solving the governing equations of the mathematical model for the shell and tube heat exchanger.

# Chapter V.

# CASE STUDIES

## V.1 Operating conditions – Case Study 1

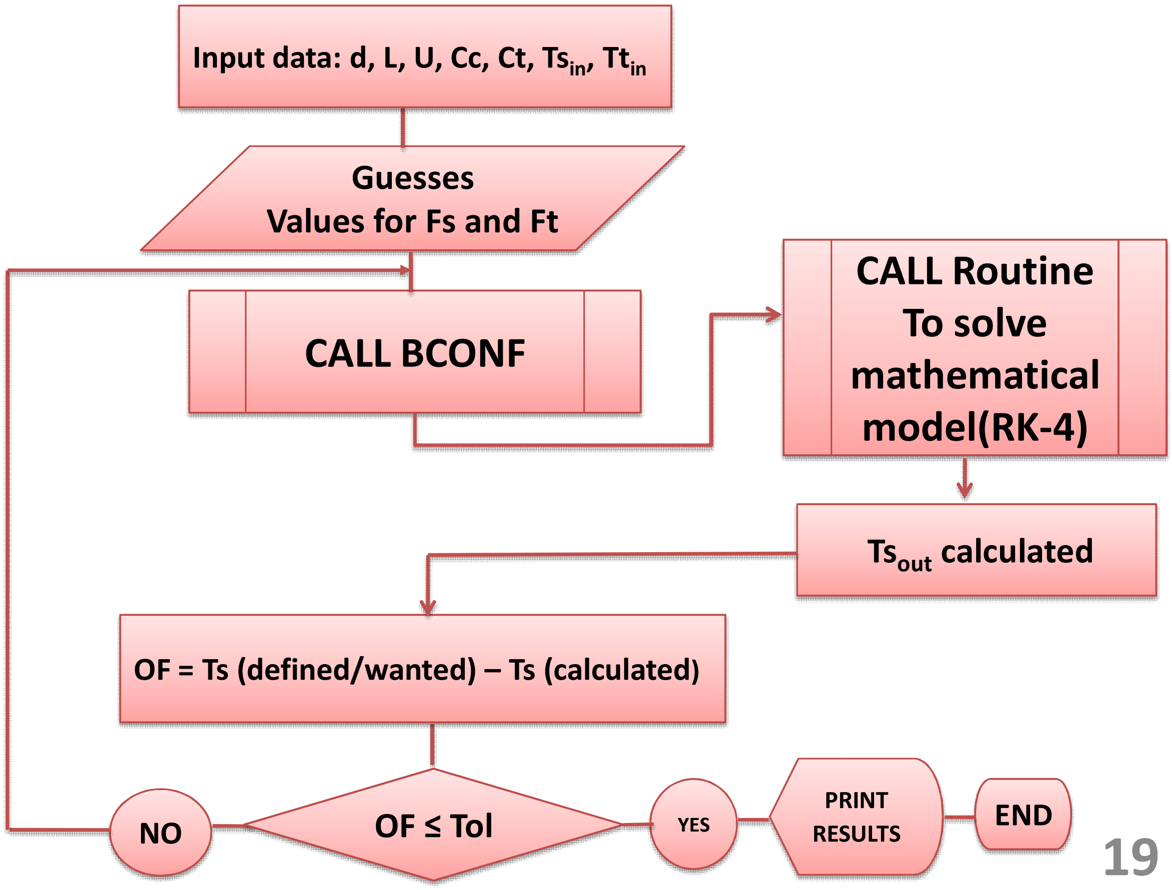
- Given the diameter (d) and the length (L) of the existing heat exchanger.
- We need to evaluate the flow rates (Ft & Fs) of each stream in order to obtain a wanted temperature (Ts out) of the cold stream at the outlet.




**Data**

1. heat capacities of the streams: Cc and Ct
2. Overall heat transfert coefficient: U
3. Tube diameter: d
4. Length of the heat exchanger: L
5. $Ts_{in}$ and $Tt_{in}$

# Flow – chart diagram



```
C***********************************************************************************
C                                MAIN PROGRAM - DRIVER                             *
C                                     CASE-STUDY 1                                 *
C***********************************************************************************
C this program is used for the operating conditions of a heat exchanger using
C optimization techniques
C in this case: finding the shell side flow rate (fs=x(1)) and the the
C tube side flow rate (ft=(x2))
C such that the output temperature from shell side (hot stream:ts1) is equal to 110°C
      INTEGER N
      PARAMETER (N=2)
C
      INTEGER IPARAM(7), ITP, L, NOUT
      REAL F, FSCALE, RPARAM(7), X(N), XGUESS(N),
     & XLB(N), XSCALE(N), XUB(N)
      EXTERNAL BCONF, FONCTION, UMACH
C
C initial values XGUESS of the parameters (fs=x(1)) and (ft=x(2)) with upper and lower bounds
      DATA XGUESS/100.0E0, 80.0E0/
      DATA XLB/50.0E0, 50.0E0/, XUB/1000.0E0, 1000.0E0/
C
C Default parameters are used
      DATA XSCALE/2*1.0E0/, FSCALE/1.0E0/
      IPARAM(1) = 0
C All the bounds are provided
      ITP = 0
C Call of the IMSL subroutine BCONF
      CALL BCONF (FONCTION, N, XGUESS, ITP, XLB, XUB, XSCALE, FSCALE,
     & IPARAM, RPARAM, X, F)
C Print results
      CALL UMACH (2, NOUT)
      WRITE (NOUT,99999) X, F, (IPARAM(L),L=3,5)
C
99999 FORMAT (' The solution is ', 6X, 2F8.3, //, ' The function ',
     & 'value is ', F8.3, //, ' The number of iterations is ',
     & 10X, I3, /, ' The number of function evaluations is ',
     & I3, /, ' The number of gradient evaluations is ', I3)
C
      END
C
      SUBROUTINE FONCTION (N, X, F)
      INTEGER N
      REAL X(N), F
      call rk(x,n,ts1)
      F = abs(110.0-ts1)
      WRITE(*,*)'OF=',F
C
      RETURN
      END
C***********************************************************************************
C                         RESOLUTION OF THE MATHEMATICAL MODEL                     *
C                             RUNGE-KUTTA METHOD - ORDER 4                         *
C***********************************************************************************
C used to solve the differential equations governing heat exchange in a tube/shell exchanger*
C                                     CASE-STUDY 1                                 *
C***********************************************************************************
      subroutine rk(x,n,ts1)
C
      real k(2,4),x(n)
      data ts0,tt0,u,cs,ct,d,xmax,h/150.0,50.0,1250.0,1.0,
     &                            1.0,0.1,1.0,0.1/
      f1(ts,tt) = -(3.14*u*d*(ts-tt))/(x(1)*cs)
      f2(ts,tt) =  (3.14*u*d*(ts-tt))/(x(2)*ct)
      xa=0.00
C
      m=inint((xmax-xa)/h)
      do 10 i=1,m
        k(1,1) =h*f1(ts0,tt0)
        k(2,1) =h*f2(ts0,tt0)
C
        k(1,2)=h*f1(ts0+k(1,1)/2.,tt0+k(2,1)/2.)
        k(2,2)=h*f2(ts0+k(1,1)/2.,tt0+k(2,1)/2.)
C
        k(1,3)=h*f1(ts0+k(1,2)/2.,tt0+k(2,2)/2.)
        k(2,3)=h*f2(ts0+k(1,2)/2.,tt0+k(2,2)/2.)
C
        k(1,4)=h*f1(ts0+k(1,3),tt0+k(2,3))
        k(2,4)=h*f2(ts0+k(1,3),tt0+k(2,3))
C
        ts1= ts0 + (k(1,1)+2.0d0*k(1,2)+2.0d0*k(1,3)+k(1,4))/6.0d0
        tt1= tt0 + (k(2,1)+2.0d0*k(2,2)+2.0d0*k(2,3)+k(2,4))/6.0d0
C
         xb=xa+float(i)*h
           ts0= ts1
           tt0= tt1
      write(*,600)xb,ts1,tt1
600   format(10x,'x=',d10.3,3x,'ts=',d25.15,/,25x,'tt=',d25.15)
10    continue
      return
      end
```

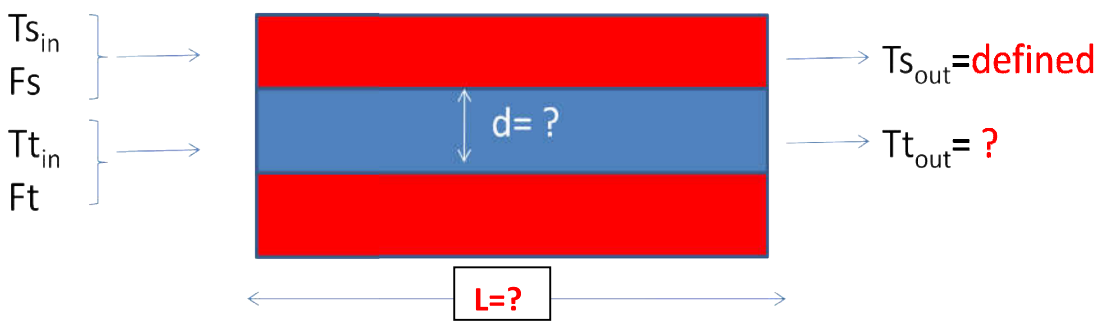
# RESULTS

# Case Study 1

<table>
<tr><th>CASE STUDIES</th><th>DATA</th><th>WANTED VALUES</th><th>CALCULATED OPERATING CONDITIONS</th></tr>
<tr><td rowspan="4">Operating conditions</td><td>Diameter : d=0.1m</td><td rowspan="4">Outlet temperature shell side : Tsout = 110 °C</td><td rowspan="2">Constraints : 50 < Ft<1000<br><br>Flow rate stream tube side : Ft = 71.218</td></tr>
<tr><td>Length : L= 1m</td></tr>
<tr><td>Inlet tube side temperature: Ttin=50°C</td><td rowspan="2">Constraints : 50 < Fs<1000<br><br>Flow rate stream shell side : Fs =106.807</td></tr>
<tr><td>Inlet shell side temperature : Tsin=150°C</td></tr>
</table>

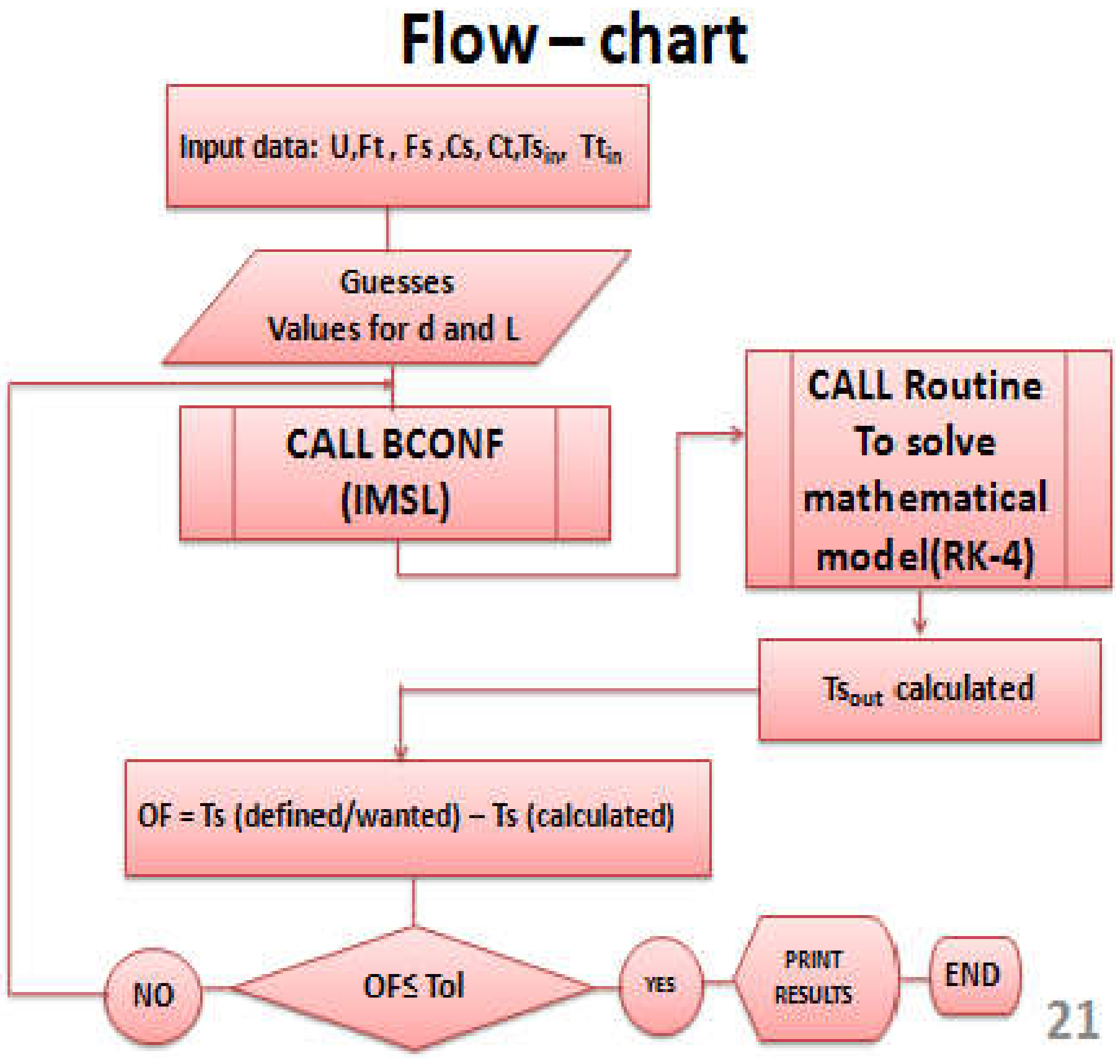
## V.2. Design of heat exchanger – Case Study 2

– The sizing of the heat exchanger
  - Given the operating conditions such as flow rates of each stream and inlet temperatures.
  - We need to evaluate the diameter of tube (d) and the length (L) of the heat exchanger in order to obtain a wanted temperature, for example, from the shell side (Tsout).
  - It is obvious that we must have constraints on the sizing of the heat exchanger.




**Data**

1. heat capacities of the streams: Cc and Ct
2. Overall heat transfert coefficient: U
3. $Ts_{in}$ , $Tt_{in}$ , Fs, and Ft


Flow – chart
Input data: U,Ft , Fs ,Cs, Ct,Ts_in, Tt_in
Guesses
Values for d and L
CALL BCONF
(IMSL)
CALL Routine
To solve
mathematical
model(RK-4)
Ts_out calculated
OF = Ts (defined/wanted) – Ts (calculated)
NO
OF≤ Tol
YES
PRINT
RESULTS
END
21

```
C*****************************************************************************************
C                                 MAIN PROGRAM - DRIVER                                  *
C                                       CASE-STUDY 2                                     *
C*****************************************************************************************
C this program is used for the design of a heat exchanger using optimization techniques
C in this case: finding the diameter(d=x(1)) and the length (L=(x2))
C such that the output temperature from shell side (hot stream:ts1) is equal to 110°C
      INTEGER N
      PARAMETER (N=2)
C
      INTEGER IPARAM(7), ITP, L, NOUT
      REAL F, FSCALE, RPARAM(7), X(N), XGUESS(N),
     & XLB(N), XSCALE(N), XUB(N)
      EXTERNAL BCONF, FONCTION, UMACH
C initial values XGUESS of the parameters (d=x(1)) and (L=x(2)) with upper and lower bounds
      DATA XGUESS/0.05E0, 0.5E0/
      DATA XLB/0.01E0, 0.8E0/, XUB/0.1E0, 1.5E0/
C Default parameters are used
      DATA XSCALE/2*1.0E0/, FSCALE/1.0E0/
      IPARAM(1) = 0
C All the bounds are provided
      ITP = 0
C Call of the IMSL subroutine BCONF
      CALL BCONF (FONCTION, N, XGUESS, ITP, XLB, XUB, XSCALE, FSCALE,
     & IPARAM, RPARAM, X, F)
C Print results
      CALL UMACH (2, NOUT)
      WRITE (NOUT,99999) X, F, (IPARAM(L),L=3,5)
C
99999 FORMAT (' The solution is ', 6X, 2F8.3, //, ' The function ',
     & 'value is ', F8.3, //, ' The number of iterations is ',
     & 10X, I3, /, ' The number of function evaluations is ',
     & I3, /, ' The number of gradient evaluations is ', I3)
C
      END
C
      SUBROUTINE FONCTION (N, X, F)
      INTEGER N
      REAL X(N), F
      call rk(x,n,ts1)
      F = abs(110.0-ts1)
      WRITE(*,*)'OF=',F
C
      RETURN
      END

C*******************************************************************************************
C                         RESOLUTION OF THE MATHEMATICAL MODEL                             *
C                             RUNGE-KUTTA METHOD - ORDER 4                                 *
C*******************************************************************************************
C used to solve the differential equations governing heat exchange in a tube/shell exchanger*
C                                    CASE-STUDY 2                                          *
C*******************************************************************************************
C
      subroutine rk(x,n,ts1)
C
      real k(2,4),x(n)
      data ts0,tt0,u,cs,ct,fs,ft,h/150.0,50.0,1250.0,1.0,
     &                                 1.0,100.0,70.0,0.1/
      f1(ts,tt) = -(3.14*u*x(1)*(ts-tt))/(fs*cs)
      f2(ts,tt) =  (3.14*u*x(1)*(ts-tt))/(ft*ct)
      xa=0.00
C
      xmax=x(2)
      m=inint((xmax-xa)/h)
      do 10 i=1,m
        k(1,1) =h*f1(ts0,tt0)
        k(2,1) =h*f2(ts0,tt0)
C
        k(1,2)=h*f1(ts0+k(1,1)/2.,tt0+k(2,1)/2.)
        k(2,2)=h*f2(ts0+k(1,1)/2.,tt0+k(2,1)/2.)
C
        k(1,3)=h*f1(ts0+k(1,2)/2.,tt0+k(2,2)/2.)
        k(2,3)=h*f2(ts0+k(1,2)/2.,tt0+k(2,2)/2.)
C
        k(1,4)=h*f1(ts0+k(1,3),tt0+k(2,3))
        k(2,4)=h*f2(ts0+k(1,3),tt0+k(2,3))
C
        ts1= ts0 + (k(1,1)+2.0d0*k(1,2)+2.0d0*k(1,3)+k(1,4))/6.0d0
        tt1= tt0 + (k(2,1)+2.0d0*k(2,2)+2.0d0*k(2,3)+k(2,4))/6.0d0
C
         xb=xa+float(i)*h
          ts0= ts1
          tt0= tt1
      write(*,600)xb,ts1,tt1
600   format(10x,'x=',d10.3,3x,'ts=',d25.15,/,25x,'tt=',d25.15)
10    continue
      return
      end
```

**RESULTS**

# Case Study 2

| CASE STUDIES | DATA | WANTED VALUES | CALCULATED DESIGN VALUES |
|---|---|---|---|
| **Design of heat exchanger** | Inlet tube side Flow rate : **Ft = 70 kg/h** | Outlet temperature shell side : **Tsout = 110 °C** | Constraints : 0.5< **L**<1.5<br>Length of the heat exchanger : **L = 0.8 m** |
| | Inlet shell side flow rate: **Fs = 100 kg/h** | | |
| | Inlet tube side temperature : **Ttin= 50 °C** | | Constraints : 0.01< **d**<0.1<br>Diameter of tube side : **d = 0.047 m** |
| | Inlet shell side temperature : **Tsin= 150 °C** | | |

## Conclusion

The purpose of this research was to analyze how to implement optimization techniques with constraints to the design and operating conditions of heat exchangers which enable us to make the best effective design relative to the set of our prioritized criteria or constraints.

The case studies presented in this report are for a simple shell-tube heat exchanger with a simple mathematical model solved numerically. However, this approach can be applied to any type of heat exchanger or any type of unit operations provided that mathematical models are developed with analytical or numerical solutions.

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