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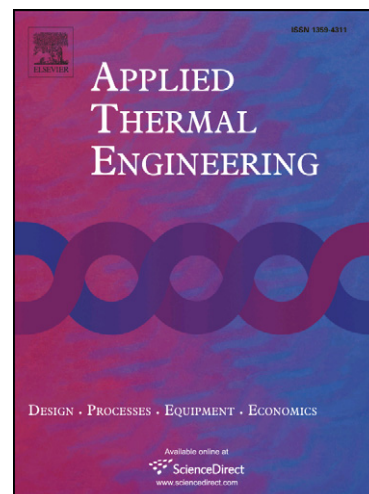
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**An algorithm for designing a TEMA 'J'-shell and tube partial condenser**María G. Camprubí, José M<sup>a</sup> Marín<sup>\*</sup>, Luis Serra

I3A – Dpt. Ingeniería Mecánica, María de Luna, s/n, Campus Río Ebro- ed. Betancourt,  
50018 Zaragoza (Spain)

**Abstract**

This paper presents an algorithm to design and calculate a rather infrequently used type of heat exchanger, the 'BJM' shell and tube partial condenser. The algorithm was developed in a project aimed at the recovery of water and energy in a chemical plant, where gases originated from drying processes contain a high quantity of water vapour with a temperature that allows the heating of some service flows. The heat transfer process implies the condensation of water vapour in the presence of non-condensable gases. Whereas the design procedure of this equipment has not yet become well established, the authors, using previous theoretical grounds, have developed a new algorithm.

**Keywords:** partial condensation, non-condensable gases, shell-and-tube condenser ,  
TEMA 'J'- shell.

**Nomenclature**

- c column number  
i number of the sector on study  
j following sector number of the i-sector gas flow  
NB number of baffles  
NC number of matrix columns

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<sup>\*</sup> Corresponding autor. Tel.: +34 976762793; fax: +34 976762616; e-mail: jmm@unizar.es

NS number of sectors  
NT number of tube passes  
r row number

## 1. Introduction

This paper discusses the design of a two-phase shell and tube heat exchanger in a basic chemical factory, where the main products are zeolite, silica and sodium silicate. The first two products must be dried before leaving the plant and the drying processes are accomplished using jet dryers with natural gas burners, generating three flows of gases with high water vapour content and dew temperatures between 62 and 63 °C.

Using air or water flows at ambient temperature these gases can be cooled to approximately 25°C, making the recovery of energy and water possible. The delivered heats are indicated in table 1, showing a great offering of energy at a very low thermal level. Furthermore, the major part of this energy recovery potential is linked to a significant water recovery potential. Since most of the factory heat requirements are at high temperature levels, the best way to take benefit from the flue gases enthalpy consists in preheating either the combustion air or the boiler feedwater, to reduce the natural gas consumption of the boiler. Another option would be to heat the water used to wash the existing filter cakes, to reduce the filter water demand.

In summary, three heat recovery systems have been designed to match three low-grade heat sources and three flows of low-degree heat demand found in the plant.

## 2 . Recovery system design

The composition and temperature of the three hot gas flows are very similar, thus the design procedure will be the same for the three systems. Due to the condensation of the water vapour contained in the flue gases, two options to design the recovery

system are being proposed: (1) A one heat exchanger configuration, based on a single two-phase heat exchanger (Figure 1); (2) A two heat exchanger configuration, based on a single-phase heat exchanger, in which only sensible heat is transferred, and on a partial condenser in which the gas flow latent heat is transferred (Figure 2). Option (2) was chosen for the following reasons: (i) Volumetric flows are substantial, thus one single exchanger would be very big in size; whereas two exchangers would be smaller and thus easier to place in the plant as well as cheaper due to a better fit to the manufacturer's standards; (ii) The presence of non-condensable gases causes the average temperature difference between the hot and cold fluids in the single heat exchanger condensing zone to be inferior than in the two exchangers case.

### **3 . Partial condensation theory**

Before continuing with the procedure devised to design the condenser, the theoretical models used for the partial condensation should be mentioned. The iterative procedure used to compute heat transfer in partial condensation is the Colburn – Hougen method [1]; this technique is considered to be the most accurate for this type of problems, with an accuracy close to 10%: thus, the algorithm presented in this paper is based on this method. More detailed information can be found in reference [2] and alternative less accurate methods can be found in references [3]-[6].

### **4 . Equipment design**

As mentioned in section 2, each recovery system is constituted by two heat exchangers; the single-phase heat exchanger is designed according to the usual TEMA standards [8]. This paper's contribution regards the design and computation of the partial condenser; therefore the following procedure is proposed.

#### 4.1 Configuration selection

An assessment of fluids, temperatures, pressure, corrosion, fouling and other relevant features to heat exchangers design leads to the determination of the condenser configuration [2]. A horizontal TEMA 'J'- shell and tube condenser was chosen for this case (Figure 3).

Figure 3 displays how the condensing gases enter the exchanger by two separate valves located at each end of the top of the tube bank, flowing to the center of the tube; this configuration admits a large volumetric flow of the condensing gases, which is the case in this study. The condensate is extracted through a valve located in the center of the shell bottom and the non-condensing gases are extracted through the top of the shell. The main advantages of this geometry include a low head loss and the easy extraction of non-condensable gases; its disadvantages are the non counter-flow fluid circulation and the possibility of vapour collapsing, in the case of non- equilibrated thermal load in the two halves of the exchanger.

A questionnaire [ 1] assists with the selection of the tubesheet (stationary or floating) and the front and rear ends. In this case the external fluid is foul but since chemical cleaning is allowed, stationary tubesheets were chosen; the internal fluid is always clean, therefore B front end and M rear end are chosen, resulting in TEMA designation BJM.

#### 4.2 Thermal design

In reference [ 2] the Colburn-Hougen method is applied to a counterflow condenser and is not valid for the TEMA BJM arrangement, in which counterflow conditions do not exist. For this reason a new algorithm was devised. An arrangement of this condenser is presented in Figure 4, with a display of both flow streamlines. The number of baffles will always be odd to ensure the essential symmetry required to balance the thermal

load on both sides of the exchanger. The tube bank is divided into a number of sectors equal to the solution of equation (1). In each sector the fluid properties were considered to be constant. The number of sectors is important because it determines the accuracy of the calculated heat transfer area; reference [7] recommends a number above seven. As in a TEMA- J shell a minimum of two tube passes is required, eight sectors are therefore obtained with just three baffles, fulfilling the recommendation.

$$NS = NT (NB + 1) \quad (1)$$

As Figure 4 shows, the sectors are numbered following the trajectory of the fluid inside the tubes. Since the gases flowing between the shell and the tube bank travel by different paths, an algorithm is required to establish the j-sector destination of the gases originating from any i-sector.

#### 4.3 Search algorithm for sector j

“Search algorithm for sector j” consists of the following three steps. [9]

*Step 1.-* Search for the i-sector coordinates, (r ,c):

The layout of the sector is compared with a two – dimensional matrix (tube pass number, baffle number plus one). The number of any sector is linked one-to-one to the sector coordinates, which allows for the calculation of (r, c), essential parameters for the Search algorithm for sector j.

The row number, r , of any i-sector is calculated using equation (2)

$$r = Floor\left(\frac{i-1}{NC}\right) + 1 \quad (2)$$

where Floor() is a function that returns the next lowest integer value, rounding down if necessary.

Since the inner fluid enters by the left side, it is directed to the right side if the row number is odd and to the left, if it is even. As sectors are numbered in an increasing order following the internal fluid flow, the column number search

algorithm depends on the row to which the sector belongs. If  $r$  is even, then the column number,  $c$ , of any  $i$ -sector is calculated according to equation (3); if  $r$  is odd, then equation (4) must be used.

$$c = NC + 1 - (i - (r - 1)NC) \quad (3)$$

$$c = i - (r - 1)NC \quad (4)$$

*Step 2.- Identification of gas stream:*

From this point, the gas stream that enters the condenser by the left side is called Left-Side Gas Stream, and the one that enters by the right side is the Right-Side Gas Stream. Due to the shell symmetry, the Search algorithm for sector  $j$  must distinguish between both streams using equations (5) and (6).

$$c \leq \frac{NC}{2} \Rightarrow \text{Left-Side Gas Stream} \quad (5)$$

$$c > \frac{NC}{2} \Rightarrow \text{Right-Side Gas Stream} \quad (6)$$

As a Left-Side Gas Stream enters, if the column number is odd, the gas flow descends; if the column number is even, the gas flow ascends. On the contrary, Right-Side Gas Stream gases descend if the column number is even and ascend if the column number is odd.

Having identified the  $i$ -sector coordinates ( $r, c$ ) and the kind of stream on study, it is possible using table 2, to characterize the  $i$ -sector according to two criteria: (i) The direction (Upwards or downwards) of the gas stream going through the  $i$ -sector; (ii) The direction (Left or right) of the inner fluid going through the  $i$ -sector.

*Step 3.- Identification of the  $j$ -sector:*

Once all parameters for the  $i$ -sector are known, the  $j$ -sector number can be calculated using the equations given in table 2.

#### 4.4 Thermal design algorithm for TEMA 'J'-shell and tube partial condenser

In order to design a horizontal TEMA 'J'-shell and tube partial condenser the Colburn-Hougen method is locally applied to each one of the sectors previously defined in section 4.2. If the input temperatures of both fluids are known for each sector, the heat transfer analysis calculates both output temperatures. Since only the inlet temperatures to the exchanger are known, the properties of the external gases are known only at both inlets. Because of how the sectors are numbered, the inner fluid output temperature for any  $i$ -sector is the inlet temperature at the  $(i+1)$ -sector, but when external gases flow from sector  $i$  to  $j$ , if  $j > i+1$  then the gas inlet temperature for the  $(i+1)$ -sector is unknown and must be guessed.

The gas inlet temperatures in all sectors are initially supposed to be equal to that of the external gases entering the condenser. This hypothesis is only valid for 1-sector and NC-sector, where both condenser inlet valves are located.

The program advances from 1-sector to NS-sector, obtaining the outlet temperature and properties of both fluids for all sectors, by applying the Colburn-Hougen method locally. Each time the program solves a sector, the outgoing gas temperatures obtained for each  $i$ -sector are taken as the new inlet temperature for the next  $j$ -sector ( $j$  is obtained as explained in section 4.3). To eliminate the influence of the guessed value in the final result, an iterative algorithm is applied.

Being NS the previously established number of sectors of the condenser, there will be NS gas inlet temperatures, of which initially only two are known; after the initial program execution only the outlet temperature of sector 1 can be reliably calculated.

In order to eliminate all guessed temperatures,  $(NS-2)$  iterations are required, executing the entire program for each one of them.

At this point, another iteration is required to eliminate the influence of the last guessed value calculated during iteration  $(NS-2)$  for the inside fluid temperatures. As a result of iteration  $(NS-1)$ , the temperatures for both fluids at all sectors are no longer influenced

by the initial suppositions. The last adjustment occurs to the inner fluid temperatures while running the (NS-1) iteration, which affects and readjusts all condenser temperatures while executing the program one more time, obtaining a solution free of supposition influences.

In further iterations no more readjustments will take place so the solution reached in iteration number NS will remain constant. A broader explanation is given in reference [9]

## 5. Geometrical design

The sizing of all condenser elements follows the TEMA standards. The key element is the appropriate shell size selection in order to obtain a rather low gas velocity ( $\approx 5.5$  m/s) so as not to impede mass transfer processes and to reduce the head losses (and in consequence the power pumping). Of utmost importance is an accurate gas velocity calculation through the tube bank, and to reach this goal not only the maximum number of tubes that can be packed into the shell must be known [7]-[10], but also the number of rows and columns in which they are distributed. For this purpose the authors have developed their own algorithm based on geometrical considerations, and implemented in an excel sheet.

## 6. Conclusions

Sections 4.3 and 4.4 present an algorithm for designing a TEMA 'J'- shell and tube partial condenser. An important criterion to decide the cost effectiveness of these heat exchangers is the comparison of the waste heat recovery with the pumping power; in both heat exchanger cases the pumping power, calculated as established in references [11] - [15] is noticeably lower.

The algorithm was implemented using the software “Engineering Equation Solver” with a computing time between one and three hours on a Pentium IV processor running at 500 MHz; with the new duo and quad core processors the computing time should be noticeably reduced. The procedure developed is rigorous, simple, computationally fast and valid for whatever heat exchanger with partial condensation. In addition, as explained in [9], these recovery systems have other benefits like water demands and CO<sub>2</sub> emissions reduction in drying industrial processes.

A more detailed explanation of the integrated recovery features will be given in a further article, currently under preparation by the authors.

### **Acknowledgments**

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## FIGURES

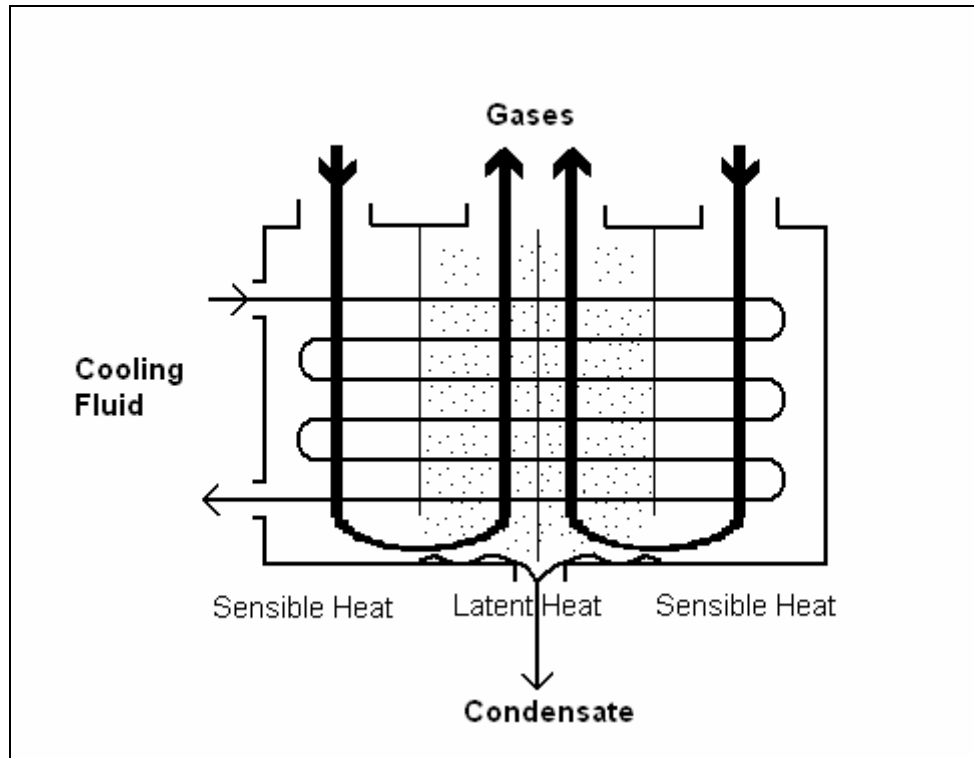


Figure 1

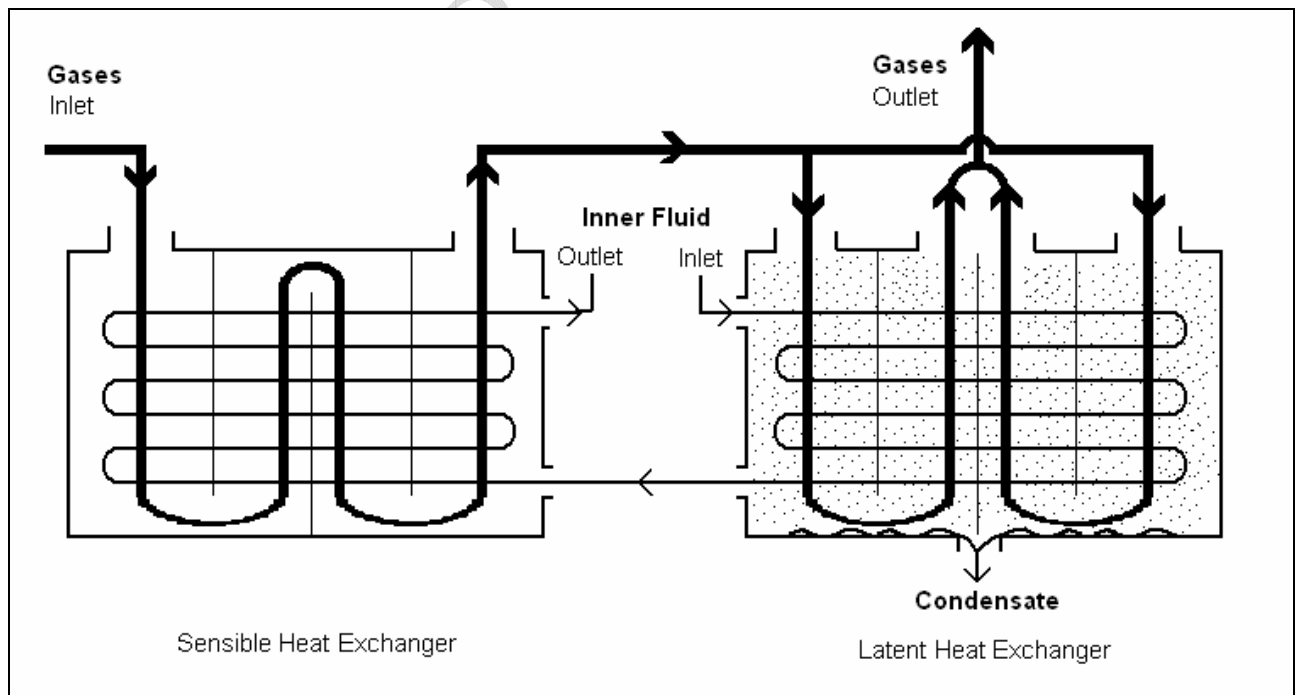


Figure 2

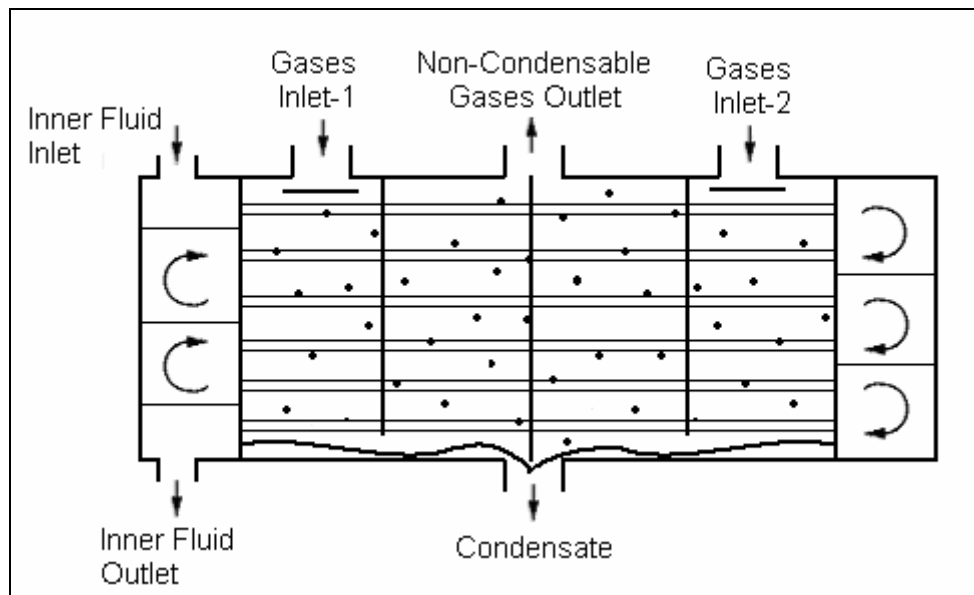


Figure 3

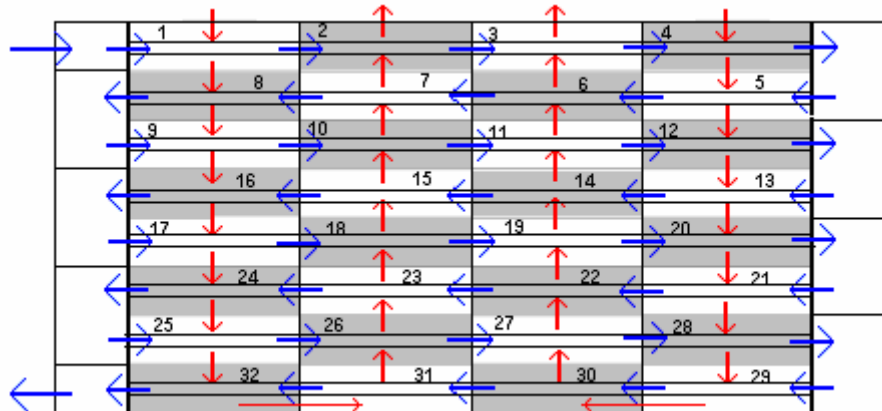


Figure 4

**Figure captions**

Figure 1.- Recovery system with one heat exchanger

Figure 2.- Recovery system with two heat exchangers

Figure 3.- TEMA 'J'-shell and tube horizontal condenser

Figure 4.- Spatial discretization in a TEMA 'J'-shell

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## Tables

Table 1 Surplus energy in the plant

Flue Gases			
T (°C)	$\dot{Q}$	quality	process
80-63,7	0,15 MW	sensible	reactors
80-62,1	0,3 MW	sensible	silica precipitation
< 63,7	3,1 MW	latent	reactors
<62,1	6,2 MW	latent	silica precipitation

Table 2. Search algorithm for sector j

CHARACTERIZATION OF SECTOR FLUIDS.	
<b>Direction of gas stream</b>	
$\text{Left Side Gas Stream } \left( c - \text{Floor} \left( \frac{c}{2} \right) \cdot 2 \right) \Rightarrow \begin{cases} =0 \Rightarrow \text{Upward} \\ \neq 0 \Rightarrow \text{Downward} \end{cases}$ $\text{Right Side Gas Stream } \left( c - \text{Floor} \left( \frac{c}{2} \right) \cdot 2 \right) \Rightarrow \begin{cases} =0 \Rightarrow \text{Downward} \\ \neq 0 \Rightarrow \text{Upward} \end{cases}$	
<b>Direction of inner fluid</b>	
$\left( r - \text{Floor} \left( \frac{r}{2} \right) \cdot 2 \right) \Rightarrow \begin{cases} =0 \Rightarrow \text{Left} \\ \neq 0 \Rightarrow \text{Right} \end{cases}$	
EQUATIONS TO CALCULATE NUMBER OF J-SECTOR	
<b>Left Side Gas Stream</b>	
Upward Right	Downward Right
$\begin{cases} r=1 \Rightarrow \begin{cases} c = NC/2 \Rightarrow j = NC \cdot NT + 1 \\ c \neq NC/2 \Rightarrow j = i + 1 \end{cases} \\ r \neq 1 \Rightarrow j = i - (c-1) \cdot 2 + 1 \end{cases}$	$\begin{cases} r = NT \Rightarrow \begin{cases} c = NC/2 \Rightarrow j = NC \cdot NT + 1 \\ c \neq NC/2 \Rightarrow j = i + 1 \end{cases} \\ r \neq NT \Rightarrow j = i + (NC - c) \cdot 2 + 1 \end{cases}$
Upward Left	Downward Left
$\begin{cases} r=1 \Rightarrow \begin{cases} c = NC/2 \Rightarrow j = NC \cdot NT + 1 \\ c \neq NC/2 \Rightarrow j = i - 1 \end{cases} \\ r \neq 1 \Rightarrow j = i - (NC - c) \cdot 2 + 1 \end{cases}$	$\begin{cases} r = NT \Rightarrow \begin{cases} c = NC/2 \Rightarrow j = NC \cdot NT + 1 \\ c \neq NC/2 \Rightarrow j = i - 1 \end{cases} \\ r \neq NT \Rightarrow j = i + (c-1) \cdot 2 + 1 \end{cases}$
<b>Right Side Gas Stream</b>	
Upward Right	Downward Right
$\begin{cases} r=1 \Rightarrow \begin{cases} c = (NC/2) + 1 \Rightarrow j = NC \cdot NT + 2 \\ c \neq (NC/2) + 1 \Rightarrow j = i - 1 \end{cases} \\ r \neq 1 \Rightarrow j = i - (c-1) \cdot 2 + 1 \end{cases}$	$\begin{cases} r = NT \Rightarrow \begin{cases} c = (NC/2) + 1 \Rightarrow j = NC \cdot NT + 2 \\ c \neq (NC/2) + 1 \Rightarrow j = i - 1 \end{cases} \\ r \neq NT \Rightarrow j = i + (NC - c) \cdot 2 + 1 \end{cases}$
Upward Left	Downward Left
$\begin{cases} r=1 \Rightarrow \begin{cases} c = (NC/2) + 1 \Rightarrow j = NC \cdot NT + 2 \\ c \neq (NC/2) + 1 \Rightarrow j = i + 1 \end{cases} \\ r \neq 1 \Rightarrow j = i - (NC - c) \cdot 2 + 1 \end{cases}$	$\begin{cases} r = NT \Rightarrow \begin{cases} c = (NC/2) + 1 \Rightarrow j = NC \cdot NT + 2 \\ c \neq (NC/2) + 1 \Rightarrow j = i + 1 \end{cases} \\ r \neq NT \Rightarrow j = i + (c-1) \cdot 2 + 1 \end{cases}$