

Application of Thermoacoustic Heat Pump Model to Distillation Columns

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Table of Contents

Table of Contents.....	1
List of Tables.....	4
List of Figures	6
Abstract	7
Declaration	8
Copyright Statement	9
Acknowledgement.....	10
Nomenclature	11
1. Introduction.....	13
1.1. General Introduction.....	13
1.2. Aim of the Dissertation	15
1.2.1. Objectives.....	15
1.3. Structure of the Dissertation.....	16
2. Background and Literature Review	17
2.1. Energy Saving Methods in Distillation	17
2.2. Heat Pumping Technologies in Industry	18
2.3. Theoretical Background of TAHP.....	21
2.4. Performance and Efficiency of TAHP	23
2.5. Important length scales in TAHP	24
2.6. Design of TAHP	26
2.6.1. Selection Working Gas	26
2.6.2. Design of TAHP Stack.....	27
2.6.3. Design of TAHP Heat Exchangers	28
2.6.4. Design of TAHP Resonator	29
2.7. Design Strategy for TAHP	29
2.8. Chapter Conclusion	30

3.	Evaluation Methodology.....	31
3.1.	Introduction	31
3.2.	Modelling of TAHP.....	31
3.3.	Selection of the Distillation Cases.....	33
3.3.1.	Azeotropic Distillation	34
3.3.2.	Sub-ambient Distillation	34
3.3.3.	Conventional Distillation	34
3.4.	Rigorous Simulation of the Distillation Columns in HYSYS	35
3.4.1.	Aspen HYSYS V7.3	35
3.4.2.	Rigorous Simulation of the Base Cases	35
3.5.	Rigorous Simulation of Compression Heat Pump in HYSYS	39
3.5.1.	Refrigerant Selection.....	39
3.5.2.	Simulation of CHP on HYSYS for the base cases	40
3.5.2.1.	Compression Heat Pump design for the Water – Methanol and Toluene – Xylene Separations	42
3.5.2.2.	Compression Heat Pump design for the Ethylene – Ethane Separations.....	43
3.6.	Chapter Conclusion	44
4.	Results and Discussion of the Results	45
4.1.	Application of TAHP Model to Distillation Columns	45
4.1.1.	Effect of Different Minimum Approach Temperatures on TAHP model Power Demand.....	51
4.1.2.	Effect of Different Working pressure on TAHP Model Power Demand	53
4.1.3.	Effect of Different Working pressure on TAHP Power Demand	54
4.2.	Application of CHP to Distillation Columns	56
4.3.	Coefficient of Performance of Thermoacoustic Heat Pump and Conventional Heat Pump.....	57

4.4.	Operating Cost Calculation of TAHP, CHP and External Utilities	57
4.5.	Discussion of Results	59
5.	Conclusions and Recommendation for Future Research.....	61
5.1.	Conclusions	61
5.2.	Recommendations for Future Research	62
6.	Bibliography	63
	Appendix A	65
	Appendix B	67



List of Tables

Table 2.1 Important physical property values for certain types of gases which are mostly used in thermoacoustic devices	27
Table 3.1 Normalized operation, working gas and stack parameters.	33
Table 3.2 Design Specification of the distillation columns	35
Table 3.3 Ethylene and Ethane polarity, electrolyte and separation pressure and temperature.....	37
Table 3.4 Toluene and Xylene polarity, electrolyte and separation pressure and temperature.....	37
Table 3.5 Water and Methanol polarity, electrolyte and separation pressure and temperature.....	38
Table 3.6 Selected working fluids (Refrigerant) for the compression heat pumps....	40
Table 3.7 Stated assumptions to carry out rigorous simulation of CHP	40
Table 3.8 Reboiler duties and Compression heat pump heat duties of the distillation base cases	41
Table 4.1 Temperature slope, cooling and heating needs of the distillation columns	45
Table 4.2 Normalized temperature difference of the distillation columns ($\Delta T_{\min}=2^{\circ}\text{C}$)	46
Table 4.3 List of working fluid (Helium) parameters for the M-W distillation.....	47
Table 4.4 List of working fluid (Helium) parameters for the T-X distillation.....	47
Table 4.5 List of working fluid (Helium) parameters for the E-E distillation	47
Table 4.6 The obtained thermal penetration depth and viscous penetration depth by solving the equations.....	48
Table 4.7 Normalized thermal penetration depth, Λ and dimensionless cooling and acoustic power for the distillation columns	49
Table 4.8 Acoustic power demand and area requirement for the application of TAHP model to the distillation columns	50
Table 4.9 Acoustic power and electrical power demand for the application of TAHP model to the distillation columns	51
Table 4.10 Power demand and area requirement of the application of TAHP model to the distillation columns at $\Delta T_{\min}=2^{\circ}\text{C}$	51
Table 4.11 Power demand and area requirement of the application of TAHP model to the distillation columns at $\Delta T_{\min}=5^{\circ}\text{C}$	52

Table 4.12 Power demand and area requirement of the application of TAHP model to the distillation columns at $\Delta T_{\min} = 8^{\circ}\text{C}$	52
Table 4.13 Power demand and area requirement of the application of TAHP model to the distillation columns at $\Delta T_{\min} = 10^{\circ}\text{C}$	52
Table 4.14 Power demand and area requirement of the application of TAHP model to the distillation columns at 10 Bar.....	53
Table 4.15 Power demand and area requirement of the application of TAHP model to the distillation columns at 20 Bar.....	53
Table 4.16 Power demand and area requirement of the application of TAHP model to the distillation columns at 30 Bar.....	54
Table 4.17 Power demand and area requirement of the application of TAHP model to the distillation columns at 400 Hz.....	54
Table 4.18 Power demand and area requirement of the application of TAHP model to the distillation columns at 800 Hz.....	55
Table 4.19 Power demand and area requirement of the application of TAHP model to the distillation columns at 1200 Hz.....	55
Table 4.20 The distillation base cases condenser and reboiler duties and associated temperatures	56
Table 4.21 Vapour compression heat pump power demand to meet external cooling and heating requirement of the distillation columns	56
Table 4.22 COP of TAHP and CHP for the base cases	57
Table 4.23 Price of HP, MP, LP and Industrial Electricity.....	57
Table 4.24 Heating and cooling requirements of the distillation columns, and power demand of the application of TAHP and CHP to the distillation base cases	58
Table 4.25 Annual operating costs of TAHP, CHP and External utilities in order to satisfy the distillation columns.....	58
Table B.1 Steam levels and physical properties.....	67
Table B.2 Stated Assumptions to calculate steam cost.....	67

List of Figures

Figure 2.1 The conventional column, integrated vapour compression heat pump (VC) and integrated vapour recompression heat pump (VRC).....	18
Figure 2.2 The temperature and heat flows in a heat pump and a heat engine	19
Figure 2.3 A typical compression heat pump consist of compressor, evaporator, condenser and a valve	20
Figure 2.4 Motion of a typical gas parcel in four steps in TAHP	22
Figure 2.5 Pressure volume diagram of a typical gas motion in TAHP.	22
Figure 2.6 The illustration of length scale of a tube.	24
Figure 2.7 A typical TAHP which consists of a tube, stack and two heat exchanger	26
Figure 2.8 Flow diagram of Tijani's TAHP design strategy.....	29
Figure 3.1 The first step of selecting a fluid package	36
Figure 3.2 Proceeding selecting a fluid package for polar and non-electrolyte components	36
Figure 3.3 Compression heat pump simulations for the distillation base cases.....	39
Figure 3.4 One stage compression and one stage pumping complex refrigeration cycle built for Toluene – Xylene and Water – Methanol separations.....	42
Figure 3.5 Two stage compression complex refrigeration cycle built for Ethylene - Ethane separation	43
Figure 4.1 Performance calculations for the stack, as function of the L_{sn} and x_n	49

Abstract

Distillation is the most popular separation method used in chemical industries. However, despite of its many known benefits and extensive use, high energy demand of the process still remains as major drawback of the distillation. Many methods of energy integration have been applied in order to moderate operating cost of distillation such as heat integration, heat pumping and thermal-coupling (Bruinsma, 2010). Heat pump technologies are one of the main energy saving technologies in distillation, efficiencies in the order of 50 % have been achieved (Bruinsma, 2010).

Various heat pump technologies assist bulk distillation columns in reducing high operating costs and capital investments. Thermoacoustic heat pumps (TAHP) are one of the novel heat pump technologies which have been studied in this dissertation.

Tijani, Zeegers et al. (2002) proposed a design strategy, which is based on linear thermoacoustic theory. The design strategy is used as a guide to design and optimize TAHP systems. The strategy proposes a dimensionless quantitative model to obtain acoustic power demand and the area requirement of TAHP. In order to conduct a proper evaluation of TAHP under different temperatures and different temperature lifts, the dimensionless model of TAHP is applied to three different distillation columns. Estimations were derived for acoustic power, electrical power and the required area for the application of TAHP to the base cases. Operating cost of TAHP is calculated based on the power demand which is also obtained from the model. The operating cost of the application TAHP to the base cases are compared with results for operating cost a conventional heat pump, vapour compression heat pump (CHP) and external utilities cost (cooling water and steam).

COP of TAHP is found to be 3 to 4 times less than CHP which illustrates that application of TAHP to the selected cases does not bring any significant benefits in terms of energy saving compared to the application of CHP methods and using external utilities. This conclusion is also supported by calculating operating cost of TAHP, CHP and external utilities, which is also states that application of TAHP model does not bring any associated benefits. It is found out to that for the above ambient distillation using external utilities is worthwhile than both application of TAHP and CHP, and for the below ambient distillation, since the process cannot be satisfied by external utilities, using CHP is necessary and worthwhile.

Declaration

This work has been submitted as partial fulfilment for the degree of MSc. in the School of Chemical Engineering and Analytical Science. No portion of the work referred to in the dissertation has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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Nomenclature

TAHP	Thermoacoustic heat pump	-
VCHP	Vapour compression heat pump	-
VRCHP	Vapour recompression heat pump	-
COP	Coefficient of performance	-
CC	Conventional Column	-
W-M	Water-Methanol	-
T-X	Toluene-Xylene	-
E-E	Ethylene-Ethane	-
HVAC	Heating, ventilation and air conditioning	-
Q_C	Cooling duty	MW
Q_H	Heating Duty	MW
T_H	Hot side temperature	K
T_C	Cold side temperature	K
T_m	Mean temperature	K
L	Length of the tube	M
p_{osc}	Oscillating pressure	Pa
x	Stack position	m
U_{osc}	Oscillating velocity	$m.s^{-1}$
C_p	Specific heat capacity of working medium at constant pressure	$J.kg^{-1}.K^{-1}$
K	Thermal conductivity	$W.m^{-1}.K^{-1}$
A	Area	m^2
W_n	Normalized acoustic power	-
Q_{cn}	Normalized cooling power	-
B	Porosity	-
D	Drive ratio	-
x_n	Normalized stack position	m
ΔT	Temperature difference	K
ΔT_{mn}	Normalized temperature difference	K
L_{sn}	Normalized stack length	m
y_o	Normalized position in y direction	m
M	Mach number	-

P_{HPS}	High pressure steam price	£.t^{-1}
P_F	Feul price	£.GJ^{-1}
		$\text{£.kW}^{-1}.\text{h}^{-1}$
P_E	Electricity price	1
P_{CW}	Cooling water price	£.t^{-1}
dH_b	Heating capacity of steam	kJ.kg^{-1}
P_{BFW}	Boiler feed water cost	£.t^{-1}
f	Frequency of the sound	Hz

Greek Letters

λ	Wavelength of the sound	m
ξ_{osc}	Displacement amplitude	m
ω	Angular Frequency	-
u_{osc}	Particle Velocity	m.s^{-1}
δ_k	Thermal penetration depth	m
δ_v	Viscous penetration depth	m
ρ_m	Mean density	Kg.m^{-3}
α	Sound velocity	m.s^{-1}
μ	Dynamic Viscosity	$\text{Kg.s}^{-1}.\text{m}^{-1}$
σ	Prandtl number	-
δ_{kn}	Normalized thermal penetration	m
γ	Polytropic coefficient	-
μ_b	Boiler efficiency	-

1. Introduction

1.1. General Introduction

Distillation is the main separation method in refineries and the chemical process industry due to its high production capacity, attractive purification characteristics, extensive use and straightforward design techniques (Bruinsma and Spoelstra, 2010). High energy demand in distillation columns (1-100 MW) and low thermodynamic efficiency (5-10 %) remains major drawbacks of the distillation (Bruinsma and Spoelstra, 2010). In general, to meet column heating and cooling requirement creates 50 % of the operating cost in food, chemical petrochemical and refining processes (Kiss, Flores Landaeta et al., 2012). A number of energy integration methods have been applied to distillation columns, in order to reduce both capital cost and operating cost such as heat integration, thermocoupling and heat pumping (Annakou and Mizsey, 1995).

A heat hump can be intruded to both a gross-root and retrofitting design without changing any process specification (Annakou and Mizsey, 1995). Therefore, heat pumping seems to be the most promising technology, which decreases energy demand of distillation column by upgrading the temperature of the condensation to the reboiler temperature to satisfy both heating and cooling requirements of the process. Additionally, since heat pump technologies reduce CO₂ emission by reducing flue gas emission, heat pump technologies are environmentally friendly (Annakou and Mizsey, 1995).

In distillation columns, heat is supplied to the reboiler, most of this heat released at lower temperature from condenser of the same column. This heat of condensation can be reused by the same column reboiler by increasing the temperature level to the reboiler temperature. A heat pump can be used to increase the temperature of condensation. Even if a CHP can be used to increase the temperature of waste heat, economical feasible application of CHP is limited to 10 to 20 °C, which is not sufficient for most distillation columns (Spoelstra, 2008). There are other types of heat pumps used in industry, such as vapour compression and vapour recompression (Bruinsma, 2010). This dissertation aims to investigate application of a novel heat pump technology, TAHP, for distillation energy savings.

A TAHP consist of four components, namely a linear motor (driver) which produces acoustic wave, a resonator which together with the associated gas (generally Helium) defines the resonance frequency and two heat exchangers on both sides of the porous regenerator (Tijani, Zeegers et al., 2002). In TAHP, acoustic power is created by electrical power input and it is converted to the thermal energy, which is a result of heat interaction between working medium and solid material. The low temperature heat from the column condenser enters the pump from the cold heat exchanger and it is upgraded by converted acoustic power. And then, the upgraded heat is rejected from the hot heat exchanger to the same column reboiler.



1.2.Aim of the Dissertation

As it is proposed by many authors, heat pumping technologies is one of the main energy saving method in bulk distillation columns (Annakou and Mizsey, 1995; Bruinsma and Spoelstra, 2010). There are many types of heat pump configuration has been proposed and used in industrial cases. In order to introduce a more energy efficient and cheaper heat pump technology, a number of researches have been carried out by many scientists and many novel heat pump technologies have been proposed.

The aim of this project is to discover viability and applicability of a novel heat pump technology, TAHP. In order to achieve aims of the dissertation, different parts of TAHP will be studied. Once the different parts of TAHP are studied, a design strategy will be applied to design a TAHP and to determine optimum working parameters TAHP. Then, the designed and optimized TAHP will be applied to different distillation columns. In order to make a general conclusion about feasibility and applicability of TAHP for different distillation columns and intensify the conclusion, application of CHP to the base cases and application of the external utilities (cooling water and steam) to the base cases will also be studied.

1.2.1. Objectives

As it is stated above, the main purpose of this dissertation is to show feasibility and applicability of the TAHP to different distillation columns and apply a quantitative model in terms of defining power demand and required area for the application of TAHP to selected bulk distillation columns. The following objectives will be studied.

- A design strategy will be adapted from the literature to study different parts of the TAHP. Fulfilling this objective will lets to understand how a TAHP works, and how to define optimal working parameters for a TAHP.
- Coefficient of performance is a performance indicator for heat pumps. In order to examine COP of TAHP, power demand of the application of TAHP to the distillation columns needs to be determined. Therefore, a quantitative model will also be obtained from the literature to define power demand of the application of TAHP.

- Different distillation processes have different heating and cooling requirements at different temperatures. To demonstrate feasibility of application of TAHP to different distillation processes, a number of distillation columns will be selected.
- TAHP, CHP and external utilities will be applied to selected distillation columns to satisfy cooling and heating requirements. From the applications power demand, heating duties and cooling duties of selected cases will be defined
- Operating cost calculation will be carried out by using obtained power demand, heating duties and cooling duties. The operating cost of the application of TAHP, CHP and external utilities will be compared with. Based on the outcome from the cost comparison a general conclusion will be made by taking into account required area for the application of TAHP.

1.3. Structure of the Dissertation

This following outlines present the work conducted during dissertation.

Section - 2 provides the associated literature review of heat pumping technologies, mainly by focusing on TAHP. Later on this section design strategy for TAHP and application of a quantitative model to TAHP is also presented.

Section - 3 provides the methodology which will be followed for this research problem and demonstrates the application of TAHP, CHP and external utilities to base cases.

Section - 4 presents the results of the application of TAHP, CHP and external utilities and provides critical evaluation of the results.

Section - 5 summarizes the work that has been carried out throughout the dissertation and draws a conclusion for the application of TAHP to distillation columns.

Automated version of power and area calculation for TAHP is presented in Appendix A.

A detailed steam and cooling water cost calculations are presented in Appendix B.

2. Background and Literature Review

2.1. Energy Saving Methods in Distillation

As it is stated above distillation is an energy intensive separation method, widely use chemical process industries (Bruinsma and Spoelstra, 2010). In order to reduce energy consumption of distillation columns, there are many energy integration methods has been applied such as heat integration, thermo-coupling and heat pumping (Annakou and Mizsey, 1995).

Heat integration is the most efficient way to reduce energy consumption of distillation columns (Smith, Jobson et al., 2010). However, the strong interactions between distillation column working parameters and heat integration limit the application of heat integration (Smith, Jobson et al., 2010). Reducing energy consumption is not the only concern while introducing an energy integration method. Operability of the altered system also needs to be assessed simultaneously together with the energy integration method (Annakou and Mizsey, 1995).

Thermally coupled designs are another energy integration method in distillation processes (Caballero, 2009). Compare to conventional distillation column, thermally coupled columns reduce both operating cost and capital cost. However, it is found by Rév, Emtir et al. (2001) and corroborated by Agrawal (2000) that Petlyuk configuration is not superior to energy integrated systems for ternary mixtures. Heat integrated design reduces number of thermally couples comparing with no-heat integrated sequences. This fact complicate the selection of the sequence since it is oppose to the heuristics, which are used point out best sequence (Caballero, 2009). Consequently, choosing the best column configuration and heat integration needs to be considered simultaneously.

Being easy to introduce and usually providing simpler operation compared to heat integration, heat pump technologies also can be considered in grass-root or retrofitting design (Annakou and Mizsey, 1995). Heat pumping systems is another economic way to moderate energy consumption of distillation columns while the temperature difference between condenser and reboiler of the column is small and the amount of heat that needs to be upgraded is high enough(Annakou and Mizsey, 1995).

2.2. Heat Pumping Technologies in Industry

In the developed countries 70-80% of energy consumption is due to process heat (Lazzarin, 1994). Since a heat pump can be used to upgrade the temperature of waste heat to desired level, knowing the level of this heat would be useful. It is stated by Lazzarin (1994) that 60 % of this heat is below 300°C and about 20-30 % is below 150°C. It is also found by Lazzarin (1994) that 2500 MW waste heat is produced in Europe due to around 850 Companies in 1987. As it can be seen from the above discussion that the amount of waste heat produces by industry is very high. While feasible application of heat pump technologies is beneficial regarding its COP and economical application, one may ask why it is still not common in industry.

Heat pumping technologies are used in distillation columns to upgrade heat of condensation releases from condenser for evaporation in the reboiler. High reboiler temperature and high temperature difference between reboiler and condenser, sometimes limit the industrial application of heat pumps due to low COP and non-economical applications.

To overcome this obstacle, two way of utilizing a heat pump is developed; vapour compression heat pump (VC) and vapour recompression heat pump (VRC) (Bruinsma and Spoelstra, 2010). Figure 2.1 demonstrates integration of VC and VRC with a conventional column.

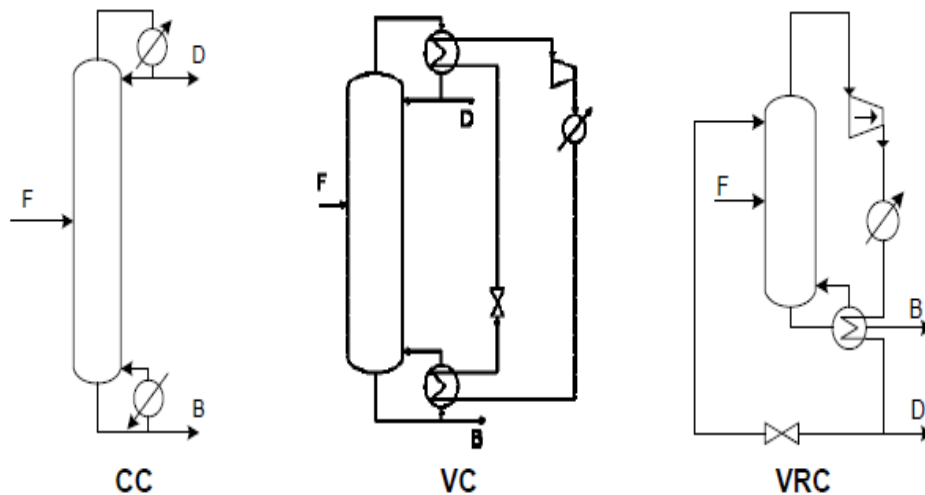


Figure 2.1 The conventional column, integrated vapour compression heat pump (VC) and integrated vapour recompression heat pump (VRC)

It can be observed from Figure 2.1 that, in the CHP a refrigerant is evaporated by removing heat from the condenser, compressed to desired level, condensed in the reboiler by rejecting its heat to the reboiler and cooled down by an expansion valve to be able to take heat from condenser and run the cycle again. In the design of the CC with the application CHP, selection of the proper refrigerant is a significant degree of freedom. VCHP is the only option, in cases where the overhead product cannot be compressed or in some novel heat pumps (Bruinsma and Spoelstra, 2010).

As it can also be seen from Figure 2.1 that the refrigerant in the VRC is the overhead vapour leaving the column, which is compressed to the desired level, condensed in the reboiler by rejecting its heat and partially refluxed to the top of column after leaving the valve, which is used to reduce the pressure of the working fluid to the desired level (Bruinsma and Spoelstra, 2010). To balance heat input in the VRC, a small condenser is required, which is the main advantage of VRC over VC. In addition to that, since VRC change heat only once, the temperature lift in VRC is about 5 K is higher than VC (Bruinsma and Spoelstra, 2010). Therefore, higher COP can be obtained for VRC. Due to these advantages VRC has turned out to be the standard technology in industry.

Heat pump systems have reverse logic with heat engine (Swift, 1988). Heat engines take high temperature heat from source, produce power and heat is rejected at low temperature. Heat pumps, on the other hand, extract low temperature heat from source and upgrade it by using power input. Figure 2.2 shown below presents the temperature and heat flows in a heat pump and a heat engine.

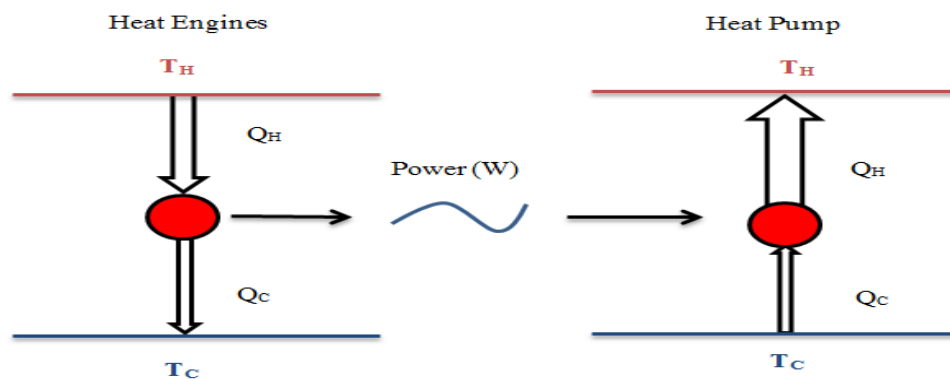


Figure 2.2 The temperature and heat flows in a heat pump and a heat engine

Heat pumps consist of four parts; evaporator, condenser, expansion valve and compressor or a pump as it is shown in Figure 2.3. Transferring and transporting heat is supplied by using a working fluid within the closed cycle of the heat pump. The cycle begins with the removing surplus heat from the heat source by evaporator. The evaporator is a place where the liquid refrigerant stores the generated energy. The working refrigerant, now in vapour form, is then transferred to the compressor. When the refrigerant is compressed, the pressure rises significantly, hence also the temperature of the refrigerant increases. The compressed (heated) refrigerant then flows to the condenser in which rejection of the surplus heat to a heat sink takes place. Due to a cooling process the refrigerants returns to liquid form, the pressure and the temperature of the refrigerant is reduced by an expansion valve, the refrigerant now can once again absorb heat from the environment. Therefore, the cycle begins once again (Ma and Chai, 2004).

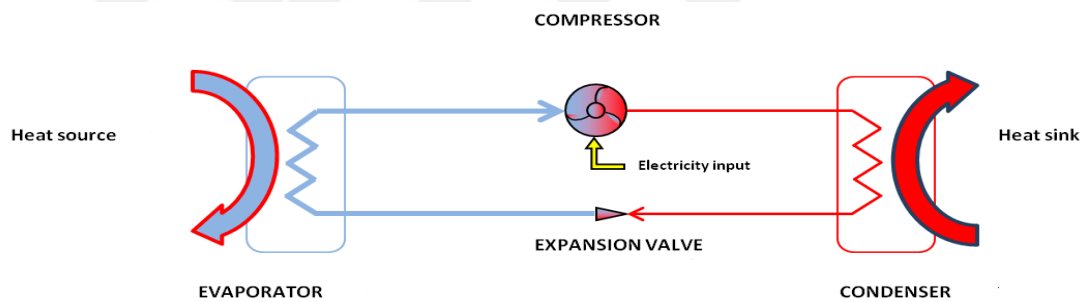


Figure 2.3 A typical compression heat pump consist of compressor, evaporator, condenser and a valve

2.3. Theoretical Background of TAHP

In TAHP, acoustic power is converted to the thermal energy in order to transport heat, generating a temperature gradient. The mechanism of the TAHP can be visualised by considering a tube containing a working medium, closed at one end and at the other end a piston moves alongside the tube, compressing and expanding the gas in the tube, as shown below in Figure 2.4 (Tijani, 2001). The movement of the piston is sinusoidal, but in order of simplicity and clarity, it will be considered as step by step cycle, as it is indicated below in Figure 2.4 by the steps (1-2-3-4-1-etc). The cycle consists of two adiabatic processes and two isobaric processes, same as Brayton cycle.

The heat pumping process happens when the temperature difference along the tube wall is zero or small. It is suggested by Tijani (2001) that the mechanism of a TAHP can be explained in four steps. In step 1, the piston moves towards the closed end in which the working medium compresses and warms up. In step 2, the compressed gas is warmer than the local wall temperature. Therefore, heat flows irreversibly from the parcel to the wall. In step 3, the piston moves back; the parcel expands and cools. In step 4, the parcel is now colder the local wall temperature. Consequently, heat transfers from the wall to the parcel. Now, since the parcel of the working medium is at the initial position, the cycle can start to work again. As a result of the piston movement a small amount of heat is transferred by the parcel of working medium from the left side to right side. A temperature slope is created along the tube after many cycles is completed. This mechanism happens as long as the temperature slope in the working medium is higher than the temperature slope along the tube wall. Net no acoustic power is used in step 1 and step 3, since work is used compressed the gas parcel in step 1 is returned in step 3. Acoustic power is consumed in step 2 and step 4 to keep pressure throughout the gas constant, while heat transfer occurs from the parcel to the tube wall. A schematic P-V diagram is shown below in Figure 2.5, where V is the volume in front of the piston. The area ABCD represents the acoustic work used during the cycle (Tijani, 2001).

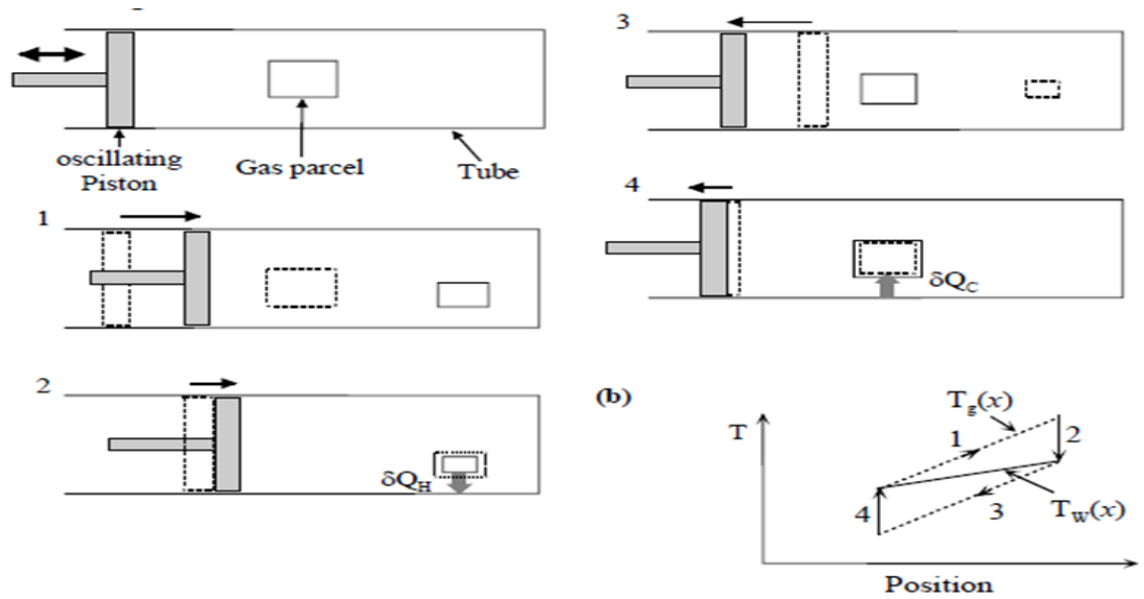


Figure 2.4 Motion of a typical gas parcel in four steps in TAHP proposed by Tijani (2001)

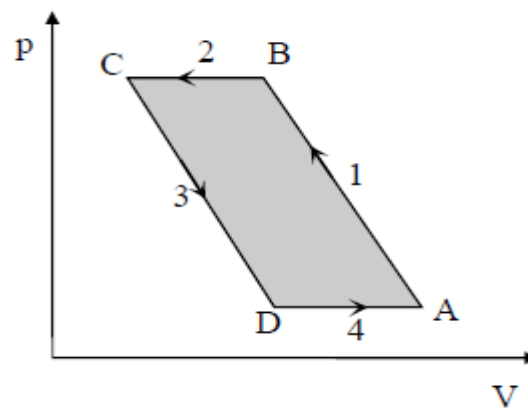


Figure 2.5 Pressure volume diagram of a typical gas motion in TAHP proposed by Tijani (2001).

Consequently, during the compression stage (step 1), the gas parcel is displaced along the tube and compressed. There are two important temperatures in the cycle; the temperature of the compressed gas parcel and the temperature of the wall. Heat flow only occurs when the temperature of the gas is higher the wall's temperature. A small temperature gradient is desired in heat pumps in order to reduce work consumption (Tijani, 2001). In the TAHP, work is absorbed in order to transfer heat from lower temperature to higher temperature. In this case, an acoustic wave has to be maintained in the tube to drive the process (Tijani, 2001).

2.4. Performance and Efficiency of TAHP

In this section the efficiency of TAHP, called coefficient of performance (COP) given by equation (2.1), will be explained. As it can be seen from Figure 2.2 that heat pumps can pump more heat than it removes from the heat source, which is stated by the first law of thermodynamics, simple energy conservation, given in equation (2.2). It means COP could be greater than 1, which is introduced as a performance indicator for TAHP.

$$COP = \frac{Q_c}{W} \quad (2.1)$$

The energy change within a process is controlled by the first and second law of thermodynamics (Tijani, 2001). In order to introduce COP, which is the ratio of the heat upgraded and transferred by the stack to the acoustic power used to accomplish the heat upgrading and transfer, the first and second laws of thermodynamics will be used. Figure 2.2 shows the temperature and heat flows in a TAHP.

The first law of thermodynamic declares that (Tijani, 2001)

$$Q_H - Q_C = W \quad (2.2)$$

The second law of thermodynamics states that the entropy generated by the process must be positive or zero (Tijani, 2001). Since the engine itself is in steady state, the net entropy increase in the reservoirs is

$$\frac{Q_H}{T_H} - \frac{Q_C}{T_C} > 0 \quad (2.3)$$

By combining equation (2.2) and (2.3), the maximum COP given by Carnot cycle, which is a formal statement of the fact that: no heat pump operating between a hot and a cold reservoir can be more efficient than a Carnot heat pump operating between same hot and cold reservoirs (Sun, Chen et al., 1997), can be found.

$$COP_{carnot} = \frac{T_C}{T_H - T_C} \quad (2.4)$$

2.5. Important length scales in TAHP

In this section some basic thermodynamic and acoustic concepts will be introduced and the effect of stack position in the standing wave field on the behaviour of TAHP will be illustrated. The length of the tube for a tube two closed ends is given by half wavelength of the sound (Tijani, Zeegers et al., 2002).

$$L = \frac{\lambda}{2} \quad (2.5)$$

The wavelength of the acoustic standing wave is determined by the velocity and frequency of the sound (Tijani, 2001).

$$\lambda = \frac{a}{f} \quad (2.6)$$

Gas displacement amplitude is another important length scale towards the motion of the working medium. The distance across which a parcel of working medium can move is twice the displacement amplitude. The displacement amplitude at a certain position along the wave oscillation direction is given by angular frequency and velocity amplitude (Tijani, 2001).

$$\xi_{osc} = \frac{u_{osc}}{\omega} \quad (2.7)$$

The displacement amplitude is generally a small portion of the stack length. Figure 2.6 shown below displays these length scales of a tube. It can be seen from the Figure 2.6 that the displacement amplitude is largest in the middle and smallest at the hard ends.

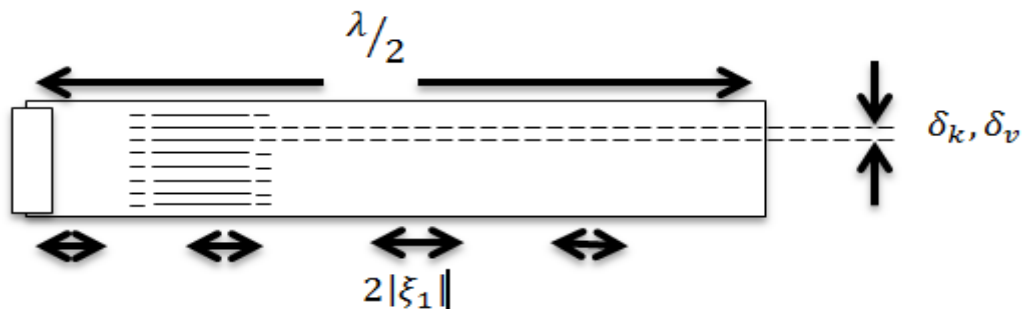


Figure 2.6 The illustration of length scale of a tube.

The particle velocity in x direction can be written as function of the position x (Tijani, 2001)

$$u_{osc} = \frac{|p_{osc}|}{\rho_m \cdot \alpha} \times \sin\left(\frac{x}{\lambda_r}\right) \quad (2.8)$$

It can be seen from equation (2.8) that the velocity of the gas parcel depends on the sound velocity, the mean density of the gas, oscillating pressure and the reduced wavelength. The velocity can also be calculated when both cross-sectional area and volume flow are known (Tijani, 2001).

$$u_{osc} = \frac{U_{osc}}{A_{total}} \quad (2.9)$$

There are two more important length scales needs to be considered, thermal penetration and viscous penetration.

Thermal penetration depth is perpendicular to the direction of the gas parcel motion in which thermoacoustic effect occurs. The thermal penetration is given by (Tijani, Zeegers et al., 2002)

$$\delta_K = \sqrt{\frac{2 \cdot K}{\rho_m \cdot C_p \cdot \omega}} \quad (2.10)$$

Viscous penetration depth can also be derived by using an analogous expression like thermal penetration depth (Tijani, Zeegers et al., 2002)

$$\delta_V = \sqrt{\frac{2 \cdot \mu}{\rho_m \cdot \omega}} \quad (2.11)$$

Prandtl number is a dimensionless parameter describing the ratio of thermal penetration depth to viscous penetration depth, which is an important parameter in thermoacoustic devices can be seen in equations (3.1) and (3.2).

The heat exchanger within thermoacoustic devices must have dimensions in order to allow heat transfer from the working gas to the tube wall, which means thermal penetration depth should as high as possible. On the other hand, in order to reduce viscous losses, the viscous penetration depth should be as small as possible (Tijani, 2001). The prandtl number then can be defined as

$$\sigma = \left(\frac{\delta_V}{\delta_K}\right)^2 = \frac{C_p \cdot \mu}{K} \quad (2.12)$$

Excluding gas mixtures, the Prandtl number for most gases (air, inert gases) is $\cong \frac{2}{3}$ (Tijani, 2001).

2.6. Design of TAHP

The performance and efficiency of a TAHP depends on several aspects and working parameters, most of which is explained in the previous sections. In this part of the dissertation, the different parts of a TAHP with their working parameters will be discussed.

A typical TAHP consist of four components which are a linear motor which produces acoustic wave, a resonator which together with the associated gas defines the resonance frequency and two heat exchangers on both sides of the porous regenerator as shown below in Figure 2.7 (Tijani, Zeegers et al., 2002). In the following paragraphs, these parts will be discussed with the working parameters and material.

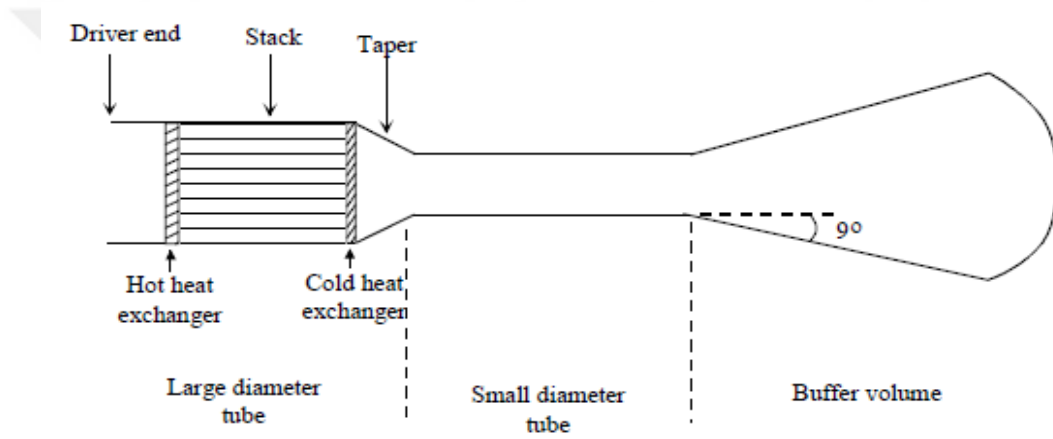


Figure 2.7 A typical TAHP which consists of a tube, stack and two heat exchangers (Swift, 1988)

2.6.1. Selection Working Gas

It can be seen in equation (2.13) that thermoacoustic power is scale as $p_m \times \alpha \times A$. In order to obtain high thermoacoustic power, a high p_m , a high α and a large A needs to be defined. Additionally, the thermal conductivity of the gas needs be high and it is known that lower Prandtl number results in lower viscous loses. For these reasons, having high sound velocity and thermal conductivity compare to air nitrogen and gas mixtures, helium is chosen as a working medium.

$$W_n = \frac{W}{p_m \cdot \alpha \cdot A} \quad (2.13)$$

Table 1, shown below, displays important physical property values for certain types of gases which are mostly used in thermoacoustic. Room temperature and atmospheric pressure are taken as the working conditions.

Table 2.1 Important physical property values for certain types of gases which are mostly used in thermoacoustic devices (Tijani, 2001).

Type of Gas	α (m/s)	ρ (kg/m ³)	C_p (J/kg.K)	K (W/m.K)	δ_v 10^{-4} (m)	δ_k 10^{-4} (m)	σ (-)
Air	343	1.19	1005	0.257	2.20	2.62	0.71
Helium	1007	0.16	5193	0.150	6.17	7.48	0.98
Nitrogen	349	1.15	1039	0.026	2.22	2.62	0.72
Helium 80% Argon 20%	602	0.46	1857	0.099	2.93	4.62	0.40
Helium 80% Xenon 20%	371	1.21	706	0.081	1.96	1.96	0.22

2.6.2. Design of TAHP Stack

In TAHP, stack is used to convert acoustic power into heat to do heat pumping. As it can be seen in Figure 2.7, stack consists of a number of parallel plates (Tijani, 2001). The amount of acoustic power that needs to be provided to upgrade the heat into desired level depends on certain characteristics of the stack such as material properties, position of the stack and stack dimensions.

Equation (2.14) shown below, which is proposed by Tijani, Zeegers et al. (2002), demonstrates relation between acoustic power and thermal conductivity and motion of gas parcel in stack region.

$$Q = -\frac{1}{4}\pi\delta_k \frac{BT_m p_1^s u_1^s}{(1+\sigma)(1+\epsilon_s)\Lambda} \left[r \frac{1+\sqrt{\sigma}+\sigma+\sigma\epsilon_s}{1+\sqrt{\sigma}} - \left(1+\sqrt{\sigma} - \frac{\delta_v}{y_0} \right) \right] - \pi[y_0 K + lK_s] \frac{dT_m}{dx} \quad (2.14)$$

It can be seen from the second term of the equation (2.14) that heat conductivity has a negative effect on the performance of the TAHP. Therefore, the stack material must have low thermal conductivity.

It is proposed by Swift (1988) and Tijani (2001) that thermal conductivity of the stack must be lower than working medium and vice versa heat capacity of the stack material must be higher than working medium in order to avoid negative effect of heat conduction thorough stack material and working medium in the stack region. Having low thermal conductivity and opportunity to produce in many thicknesses from 10 to 500 μm , Mylar, which refers to polyester films or plastic sheet, is chosen as a stack material.

2.6.2.1. TAHP Stack Geometry Design

There are many geometrical types of stack; parallel plate, pin array, circular pores, triangular pores. Rott's equation, which is the function of the ratio the hydraulic radius over thermal penetration depth, is used for preliminary selection of stack geometry. Rott's equation suggests that pin array and parallel plates are the most two promising stack geometries. Regarding fabrication reasons, parallel plates stack geometry is chosen (Tijani, Zeegers et al., 2002). Parallel plates stack must have $r_h = y_0$.

2.6.3. Design of TAHP Heat Exchangers

The heat exchangers are essential to transfer heat into or out of a process. Even though, there are many types heat exchangers for all kinds of applications exist; heat exchangers are not commonly available for TAHP. In order to improve heat transfer, the heat exchangers in TAHP should have high thermal conductivity for efficient heat transfer and enough area for efficient heat transfer (Tijani, 2001). Figure 2.7 shows that a TAHP needs one cold heat exchanger to take heat from the column condenser and one hot heat exchanger to remove pumped heat and reject it to the same column reboiler. It is proposed by Swift (1988) that the length of the heat exchangers should be equal to the peak-to-peak displacement amplitude of the working medium in the heat exchanger location. Consequently, the length of the heat exchanger can be expressed:

$$L_{hx} = 2 \cdot \xi_{osc} = 2 \cdot \frac{u_{osc}}{\omega} \quad (2.15)$$

2.6.4. Design of TAHP Resonator

The purpose of using resonator is to store acoustic power and to provide proper phasing of the velocity and pressure. The resonator needs to be designed in order to minimize the length, shape, weight and the losses. As it is stated in section 2.5, the wavelength of the sound that oscillating in a tube for a tube two closed ends is given by twice the length of the tube (Tijani, 2001).

$$\lambda = 2.L \quad (2.16)$$

The resonator tube cross-sectional area is usually circular in order to minimize losses occurs at the surface. Additionally, the losses can be decreased by a smooth and varying cross-section.

2.7. Design Strategy for TAHP

In order to define working parameters of TAHP, there is several design strategies proposed by many authors such as Swift (1988), Wetzel and Herman (1997) and Tijani (2001). The most promising and simple approach is proposed by Tijani (2001) which is being used in this project to design TAHP shown below Figure 2.8.

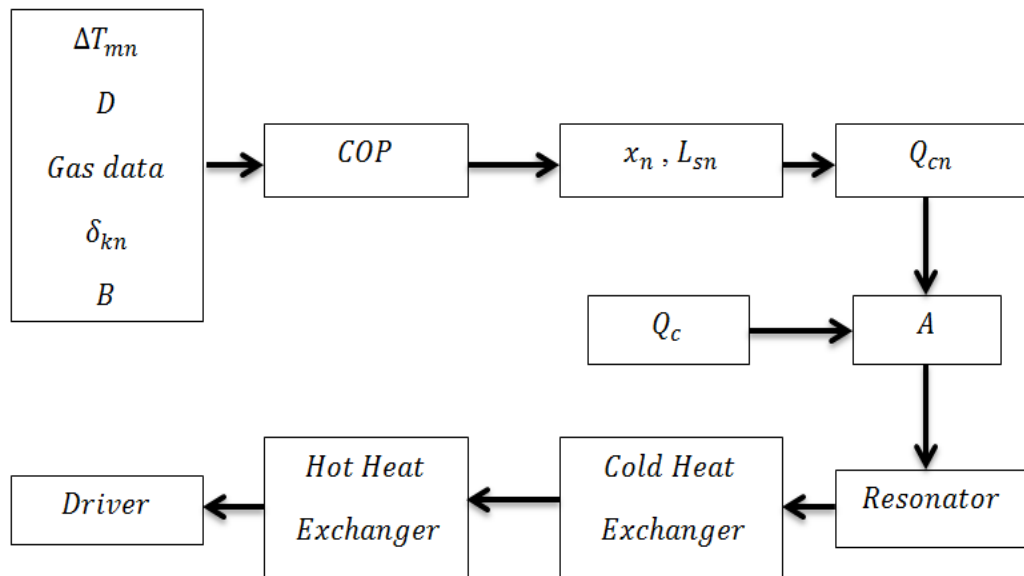


Figure 2.8 Flow diagram of Tijani's TAHP design strategy.

2.8.Chapter Conclusion

The aim of this dissertation is to study the use of TAHP in distillation context and demonstrate the potential of TAHP in terms of energy saving. The literature review has been divided into several parts.

The first topic is mainly focus on energy saving methods that has been used in industry. The second topic goes into detail in terms of use of heat pumps and types of heat pumps that has been conducted to the industrial cases.

TAHP uses acoustical power to generate heat oscillation. Therefore, explaining the working procedure of TAHP is necessary for better understanding of TAHP. The third topic of the section covers theoretical background of TAHP by mainly focusing on working procedure of TAHP.

The following other three topics focus on designing a TAHP and defining optimal working parameters of TAHP. The proposed design strategies by researchers has been investigated and the most promising and easy approach has been selected.

The last topic of the section explains the model that has been conducted thorough the project to calculate power demand and required area for application TAHP to distillation columns.

3. Evaluation Methodology

3.1. Introduction

As introduced in section 1.2, the aim of this dissertation is to assess the viability of application of TAHP to distillation columns. In this section the methodology undertaken for this dissertation is detailed. This includes first the modelling of TAHP and the relevant equations that were used to analyse the systems. Analysis was conducted by rigorous simulation of the distillation base cases (Section 3.2). To demonstrate feasibility of the TAHP in different distillation columns, a number of different base case were selected, detailed in Section 3.3. Section 3.4 details the rigorous simulation of each distillation column in HYSYS. Section 3.5 presents the rigorous simulation of the application compression heat pump to each of the base distillation cases on HYSYS.

3.2. Modelling of TAHP

The exact theoretical equations for the calculation of acoustic power and heat flow in the stack are complicated. Therefore, a simplified equation derived from the short-stack and boundary-layer approximations was implemented (Swift, 1988; Tijani, 2001; Tijani, Zeegers et al., 2002). Despite of implementation of approximations, the modified equation still complicated since it includes a large number of parameters of the working medium, material and geometrical parameters of the stack (Tijani, Zeegers et al., 2002). Having many parameters makes use of the expression complex. However, it can be further modified by using a group of dimensionless parameters. A paper is written by Olson and Swift about dimensionless parameters for thermoacoustic devices (Olson and Swift, 1994). The remaining parameters of thermoacoustic devices can be derived by using approximations suggested by Olson and Swift (1994).

It is stated in Section 2.7 that the most promising and simple design strategy is suggested by Tijani (2001). The design strategy also suggests a dimensionless quantitative model to define working parameters of TAHP such as frequency, pressure, acoustic power and required area for application of TAHP to base cases. The main equations are used to analyse gathered data are shown below in equation (3.1) and (3.2). Equation (3.1) is used to define dimensionless heat flow in the TAHP stack. Equation (3.2) is used to define dimensionless acoustic power in the TAHP stack.

$$Q_{cn} = -\frac{\delta_{kn}D^2\sin(2x_n)}{8\gamma(1+\sigma)\Lambda} \times \left(\frac{\Delta T_{mn}\tan(x_n)}{(\gamma-1)B} \frac{1+\sqrt{\sigma}+\sigma}{L_{sn}1+\sqrt{\sigma}} - (1+\sqrt{\sigma} - \sqrt{\sigma}\delta_{kn}) \right) \quad (3.1)$$

and

$$W_n = \frac{\delta_{kn}L_{sn}D^2}{4\gamma} \times (\gamma-1)B\cos^2x_n \times \left(\frac{\Delta T_{mn}\tan(x_n)}{(\gamma-1)B} \frac{1+\sqrt{\sigma}+\sigma}{L_{sn}(1+\sqrt{\sigma})\Lambda} - 1 \right) - \left(\frac{\delta_{kn}L_{sn}D^2}{4\gamma} \frac{\sqrt{\sigma}\sin^2x_n}{B\Lambda} \right) \quad (3.2)$$

where Λ is given by

$$\Lambda = 1 - \sqrt{\sigma}\delta_{kn} + \frac{1}{2} \sigma \delta_{kn}^2 \quad (3.3)$$

and

$$\delta_{kn} = \frac{\delta_k}{y_0} \quad (3.4)$$

The important parameters in thermoacoustic devices, which are contained in the dimensionless acoustic power and heat flow equations are given in Table 3.1. By using the parameters, shown in Table 3.1, Tijani (2001) dimensionless quantitative model is applied to the base cases to find the acoustic power and area requirement. According to his strategy, by first placing the parameters into equations (3.1) and (3.2), dimensionless acoustic power and heat flow can be determined. For a known cooling duty and temperature, the required area then can then be defined from the normalized cooling power equation given in Table 3.1. By placing the area into the normalized acoustic power expression, given in Table 3.1, the required acoustic power can be found.

Table 3.1 Normalized operation, working gas and stack parameters.

Operation Parameters	
Drive ratio	: $D = \frac{p_0}{p_m}$
Normalized cooling power	: $Q_{cn} = \frac{\dot{Q}_c}{p_m \times \alpha \times A}$
Normalized acoustic power	: $W_n = \frac{\dot{W}}{p_m \times \alpha \times A}$
Normalized temperature difference	: $\Delta T_{mn} = \frac{\Delta T_m}{T_m}$
Gas parameters	
Prandtl number	: σ
Normalized thermal penetration depth	: $\delta_{kn} = \frac{\delta_k}{y_0}$
Stack Geometry parameter	
Normalized Stack length	: $L_{sn} = k \times L_s$
Normalized stack position	: $x_n = k \times x$
Blockage ratio or porosity	: $B = \frac{y_0}{(y_0+1)}$

3.3. Selection of the Distillation Cases

Distillation is one of the most popular physical separation technologies in industry (Annakou and Mizsey, 1995). The types of distillation columns can be divided into several groups which are designed to successfully perform specific types of separations. These variations appear because of difficulty in separation when the physical properties of the components in a mixture close one to another, such as, azeotropic distillation. In general types of distillation can be divided in to two main groups, batch and continuous columns. In batch column feed is introduced to the column in batch-wise. On the other hand, in continuous column feed is introduced to the column continuously. Continuous distillation columns are more popular in industry and it involves separation of large quantities which accompanied with high heating and cooling demand. Therefore, in this dissertation three types of continuous distillation columns has been selected to illustrate applicability of TAHP, sub-ambient, azeotropic and conventional distillation columns. Detailed explanation of the selection of these base cases is given below.

3.3.1. Azeotropic Distillation

Azeotropic distillation column is designed to perform the separations in which relative volatilities of component are low ($0.95 < \alpha < 1.05$) (Hilal, Yousef et al., 2002). Due to low volatility of component in azeotropic distillation, the separation becomes difficult. In order to meet process separations specifications, large number of trays is required and high reflux ratio is needed as well. In another word, azeotropic distillation requires high capital investment due to large number of trays and high energy demand due to high reflux ratio which makes azeotropic distillation uneconomic. Water-Methanol separation is a typical example of Azeotropic distillation (Widagdo and Seider, 1996). In order to perform economical application of azeotropic distillation, a heat pump will be introduced in terms of energy saving.

3.3.2. Sub-ambient Distillation

Sub-ambient distillation columns take place below ambient temperature, meaning condenser temperatures always below ambient temperature. Ethylene and Ethane separation is an example of sub-ambient distillation. To run a sub-ambient distillation column, rejection of heat from the condenser requires a refrigeration cycle. In order to satisfy the column condensers' external cooling demand, compression work is required for the refrigeration cycle. This work usually contributed to majority of the power demand of the process (Smith, Jobson et al., 2010). In order to reduce the power demand and operating cost of the sub-ambient distillation column, a TAHP model will be studied for integration.

3.3.3. Conventional Distillation

Conventional distillation consists of one feed and two pure products. In order to perform separation, heat is supplied to the column reboiler at the highest temperature of the column, and heat is removed from the condenser at the lowest temperature of the column. Therefore, in order to handle the separation, conventional distillation involves the degradation of heat from high temperature level to a lower temperature level (Shenvi, Herron et al., 2010). Due to the heat degradation conventional column are usually associated with a high energy demand (Segovia-Hernández, Hernández et al., 2004). Consequently, it is another energy intensive distillation column for which introducing TAHP may prove beneficial in operation of feasibility.

3.4. Rigorous Simulation of the Distillation Columns in HYSYS

3.4.1. Aspen HYSYS V7.3

Aspen HYSYS V7.3, a process modelling and simulation software, developed by Aspen Technology, Inc, was used in this dissertation in order to define physical properties of components and modelling of distillation columns. Despite having the same basic design concept, HYSYS is chosen over Aspen Plus due to its simplicity.

3.4.2. Rigorous Simulation of the Base Cases

To carry out rigorous simulations of the selected cases, the design specifications of the columns such as feed flow rate, feed temperature, feed pressure and reflux ratio, used to control purity of products, need to be known. For the rigorous simulation of the selected distillation columns in HYSYS, three published distillation cases were assessed from Choe and Luyben (1987). Table 3.2 shown below gives the design specification of the columns.

Table 3.2 Design Specification of the distillation columns (Choe and Luyben, 1987)

Design Specification	Systems		
	Methanol- Water	Toluene- Xylene	Ethylene- Ethane
Feed flow rate g.mol/min	27240	18000	5000
Feed composition	0.5	0.67	0.5
Feed temperature °C	70	95	-7
Feed Pressure mmHg	760	90	22800
Distillate flow rate gmol/min	13620	5934	2500
Distillate composition	0.999	0.999	0.95
Reflux ratio	1.023	1.206	7.32
Number of trays	32	29	47
Feed stage	6	14	25

Rigorous simulations for the columns were carried out by following steps;

Step 1: Fluid Package: For the first step in simulating a column in HYSYS; a fluid package needs to be selected for the calculation of physical properties of the components.

A fluid package selection method is published by Carlson (1996) which suggests that the fluid package can be selected by looking the polarity and electrolyte of components and also associated pressure and temperature of separation as shown in Figure 3.1 and Figure 3.2.

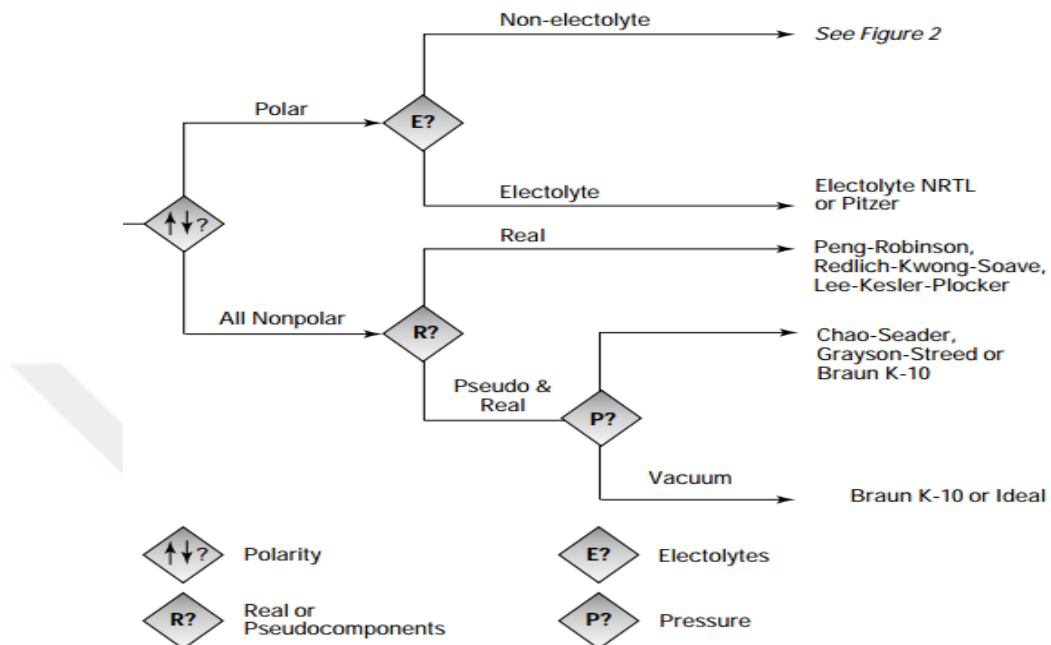


Figure 3.1 The first step of selecting a fluid package (Carlson, 1996)

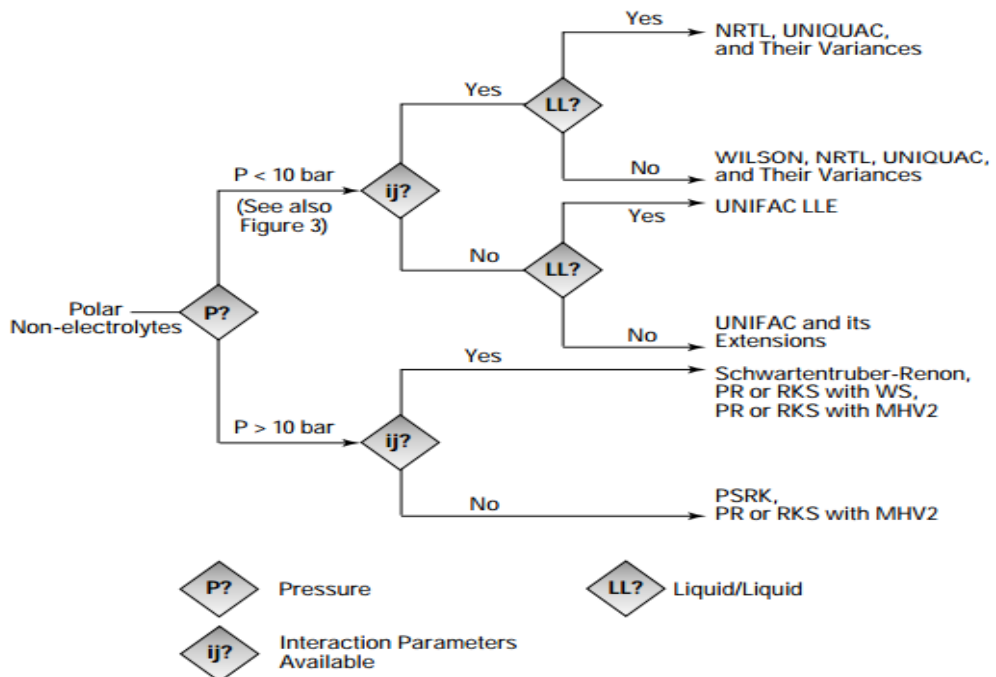


Figure 3.2 Proceeding selecting a fluid package for polar and non-electrolyte components (Carlson, 1996)

In order to determine a fluid package which suits best to define physical properties of components, polarity and electrolyte of component was carried out as introduced in Table 3.3 Table 3.4 and Table 3.5.

Table 3.3 Ethylene and Ethane polarity, electrolyte and separation pressure and temperature

Components	Polarity	Electrolytic	Temp. gradient over column (K)	Column Pressure (Bar)	Fluid Packages
Ethylene	Non-polar	Non-Electrolyte	281>T>261	>10	SRK Peng- Robinson- Lee-Kesler- Plocker
Ethane	Non-polar	Non-Electrolyte			

Table 3.4 Toluene and Xylene polarity, electrolyte and separation pressure and temperature

Components	Polarity	Electrolytic	Temp. gradient over column (K)	Column Pressure (Bar)	Fluid Packages
Toluene	Non-polar	Non-Electrolyte	379>T>371	<10	SRK Peng- Robinson- Lee-Kesler- Plocker
Xylene	Non-polar	Non-Electrolyte			

Table 3.5 Water and Methanol polarity, electrolyte and separation pressure and temperature

Components	Polarity	Electrolytic	Temp. gradient over column (K)	Column Pressure (Bar)	Fluid Packages
Water	Polar	Non- Electrolyte	374>T>338	<10	NRTL UNIQUAC
Methanol	Polar	Non- Electrolyte			

Based on the given criteria, Peng-Robinson was chosen as a fluid package for Ethylene - Ethane and Toluene - Xylene separations, and general NRTL was chosen for Water - Methanol separations.

Step 2: Adding components: For each of the cases the selected components were added.

Step 3: Creating process flowsheet: A material stream was created first based on defined feed conditions such as pressure, temperature and composition. Then, a column was inserted, material stream were set for the inlet of the column and finally the input design parameters were set.

Step 4: Component Recovery: The simulation was run and converged for two basic specifications, reflux ratio and distillate rate. To meet product purity, the component recovery specifications were set and the process was simulated again.

3.5. Rigorous Simulation of Compression Heat Pump in HYSYS

By simulating the distillation columns in HYSYS, the external heating and cooling needs were defined. In order to determine the compression and pumping work required to meet heating and cooling needs, rigorous simulations of CHP was carried out in HYSYS for each of the columns. *Figure 3.3* shown below demonstrates simulation of compression heat pump with distillation column in HYSYS.

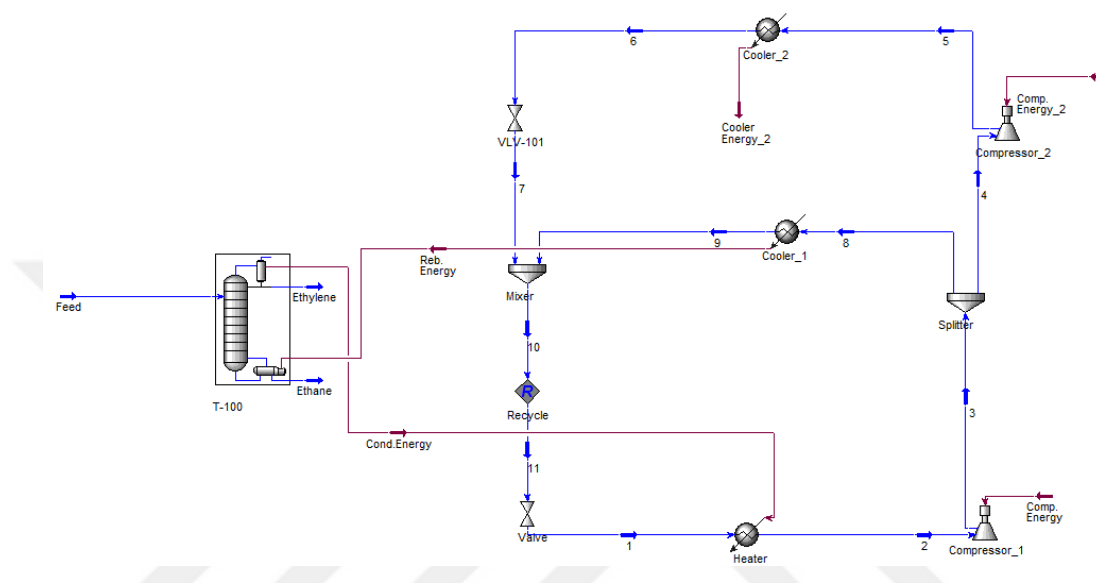


Figure 3.3 Compression heat pump simulations for the distillation base cases.

A simple Compression heat pump (simple refrigeration cycle) consists of an evaporator, condenser, expansion valve, working fluid (refrigerant) and compressor or pump depending on the degree of heating and cooling involved. To begin constructing rigorous simulation of CHP in HYSYS, a refrigerant was selected for each of the cases.

3.5.1. Refrigerant Selection

In order to transport heat within a heat pump cycle, a refrigerant is required. The first step was to carry out a rigorous simulation of the cycle in HYSYS to define compression and pumping work including an intuitive selection of refrigerant. The selected refrigerant needs to be able to take heat from the column condenser and reject it to where it requires. It means the refrigerant working temperature range has to cover both the reboiler and condenser temperature. The evaporator of the refrigeration cycle is coolest point of the cycle which needs to be able to take heat from the column condenser and satisfy the cooling requirement of the condenser.

The condenser of the same cycle is the hottest point of the cycle which needs to be able to deliver available heat to the same column reboiler and satisfy the heating needs of the reboiler. While choosing a refrigerant, there are some issues that need to be considered. For example, it is preferable to use a refrigerant which is already a component in the process that requires a minimum amount of shaft work, and most importantly does not have toxicity properties (Smith, 2005). By taking into account the general considerations, which are given above, a refrigerant was chosen for each the distillation processes shown below in Table 3.6.

Table 3.6 Selected working fluids (Refrigerant) for the compression heat pumps

Case Identifier	Refrigerant
Water – Methanol	n-Butane
Toluene – Xylene	n-Butane
Ethylene - Ethane	Propane

3.5.2. Simulation of CHP on HYSYS for the base cases

To begin the rigorous simulation of the refrigeration cycle, assumptions needed to be stated such as pressure drop, minimum approach temperature and the efficiency of the compressor. The following assumptions, shown in Table 3.7, are made while the rigorous simulation of CHP is carried out.

Table 3.7 Stated assumptions to carry out rigorous simulation of CHP

Assumptions	
1- Compressor Polytrophic Efficiency	85%
2- Pump Efficiency	85%
3- Pressure Drop in Condenser and Evaporator	0
5- $\Delta T_{\min}$ ($^{\circ}\text{C}$) over Compression heat pump cycle	5
6- Evaporator out Vapour Fraction	0
7- Condenser out Vapour Fraction	1
8- Condenser out Temperature	$T_{\text{cond.}} - \Delta T_{\min}$
9- Evaporator out Temperature	$T_{\text{Reb.}} + \Delta T_{\min}$

The obtained input data from the rigorous simulation of the distillation base cases in HYSYS were applied to carry out the rigorous simulation of CHP for each of the cases within HYSYS. The rigorous refrigeration cycle is built up by inserting the appropriate apparatus and the required heater and cooler temperatures were set with a $\Delta T_{\min}$ regulation ($\mp \Delta T_{\min}$).

The main purpose of a heat pump in the context of the distillation column is to take heat from column condenser, upgrade it to the same column reboiler temperature and reject it to the same column reboiler. A simple CHP is designed for each of the cases and associated results are shown below in Table 3.8. It is observed from the results that for the selected distillation cases; when heat is taken from the condenser and upgraded to the desired level, the amount of heat that the heat pump cycle needs to reject to the column reboiler is more than the column reboiler can take. Consequently, in order to provide continuity for both distillation columns and heat pumps, a complex cycle needs to be designed for all the selected distillation cases.

Apart from the simple refrigeration cycle, an extra cooler, pump, splitter and mixer is placed into the cycle for the above ambient distillation separations, Water – Methanol and Toluene - Xylene separations, with a cooler, splitter, mixer and compressor for the below ambient separation, Ethylene - Ethane separation. Since the compression heat pump has more heat than the reboiler can take, shown below in Table 3.8, these apparatus is used to balance the heat exchange between refrigeration cycle condenser and column reboiler.

Table 3.8 Reboiler duties and Compression heat pump heat duties of the distillation base cases

Case identifier	$Q_{\text{Cond.}}$ (MW)	$Q_{\text{Comp.}}$ (MW)	Total amount of heat that needs to be rejected $Q_{\text{Cond.}} + W_{\text{Comp.}}$ (MW)	$Q_{\text{Reb.}}$ (MW)
Water – Methanol	16.32	3.21	19.53	16.71
Toluene – Xylene	18.55	5.05	23.65	7.12
Ethylene – Ethane	0.224	0.40	0.624	0.229

3.5.2.1. Compression Heat Pump design for the Water – Methanol and Toluene – Xylene Separations

Designing of the cycle begins with the placement of an evaporator. The evaporator is used to take heat from the column condenser. It was stated in Section 3.5.2 that, the amount of heat that needs to be rejected by the refrigeration cycle is higher than the column reboiler can take. Therefore, a splitter is used to split the stream into two streams. The first stream was set as a lower cycle condenser inlet which rejects heat to the ambient. The second stream was set as an upper cycle compressor inlet which is compressed to reboiler temperature level in order to reject heat to the column reboiler. Since, the column's condenser temperatures are above ambient, a pump was placed in the lower cycle to pump the working fluid after heat rejection to the desired pressure level, for the upper cycle condenser outlet. A mixer was placed to combine the lower cycle pump outlet and the upper cycle condenser outlet before entering the expansion valve. A process flow diagram of the rigorous simulation of the heat pump cycle for the Toluene – Xylene and Water – Methanol columns in HYSYS is shown below in Figure 3.4.

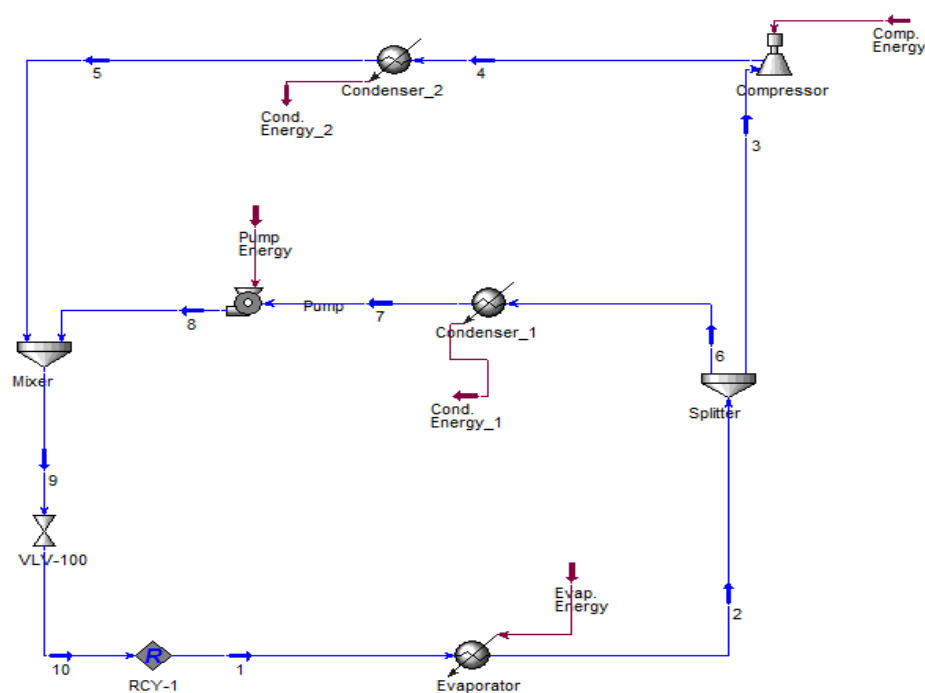


Figure 3.4 One stage compression and one stage pumping complex refrigeration cycle built for Toluene – Xylene and Water – Methanol separations

3.5.2.2. Compression Heat Pump design for the Ethylene – Ethane Separations

Same as for Toluene – Xylene and Water – Methanol separations, an evaporator was placed in order to remove heat from the column condenser. Since, the separations takes place below ambient temperature, and the amount of heat that needs to be rejected by the refrigeration cycle is higher than the column reboiler can take, a heat pump cycle needs to possess two stages of compression. The first stage of the compression is to upgrade the temperature of heat to the reboiler temperature and the second compression stage is used to upgrade the heat temperature to the ambient temperature (cooling water temperature). After the first compression stage a splitter is placed to split the compressed stream into two streams. The first stream is set as a lower cycle condenser inlet and the second is set as an upper cycle compressor inlet. An expansion valve is placed after the condenser in the upper cycle to equalize the pressure of the upper cycle to that of the lower cycle condenser outlet before its entering the mixer. An expansion valve is placed on the mixer outlet in order to meet evaporator inlet. A process flow diagram of the rigorous simulation of heat pump cycle for the Ethylene - Ethane separation on HYSYS is shown below in Figure 3.5.

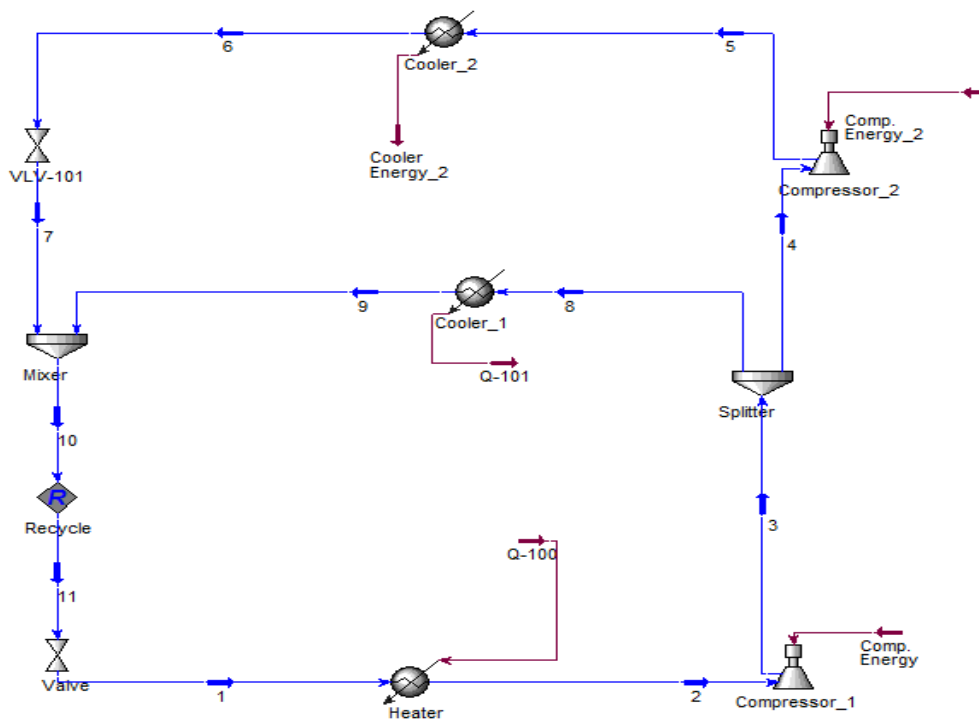


Figure 3.5 Two stage compression complex refrigeration cycle built for Ethylene - Ethane separation

3.6. Chapter Conclusion

Section three was dedicated to explain the methodology that has been followed to implement the dissertation. The section was divided into four parts.

The first topic of the section focuses on the modelling of TAHP. The topic details the selected model with the associated equations. By using the rigorous simulation of distillation columns outputs, heating and cooling needs of the columns and associated temperatures, as inputs of the TAHP model, acoustic power demand and area requirement of the application of TAHP to the distillation base cases will be determined for the evaluation of the performance of the TAHP model.

The second part of the section illustrates the selected distillation columns and the monitored reasons for the selection of the distillation columns.

The last two topics of the section present the main design tool, Aspen HYSYS version V7.3 that has been used in this work for design and simulations of the distillation columns and conventional heat pump. The topics also include the simulation methodology that has been conducted for the simulation of the distillation columns and conventional heat pump. The purpose of simulating conventional heat pump for each of the distillation base cases is to evaluate viable and economical application of TAHP. A comparison will be carried out between the results obtained from conventional heat pump and the results obtained from the TAHP model.

4. Results and Discussion of the Results

In this section of the dissertation, results of the models of TAHP, Compression heat pump and external utilities (cooling water and steam) to distillation columns are presented and associated operating cost are calculated.

4.1. Application of TAHP Model to Distillation Columns

Determination of the parameters;

1. The first step was to define the temperature slope and cooling requirement of the cases. The data shown below on Table 4.1 is obtained from the rigorous simulation of the columns on HYSYS.

Table 4.1 Temperature slope, cooling and heating needs of the distillation columns

Case	T _{Reb.} (K)	T _{Cond.} (K)	Q _{Reb.} (MW)	Q _{Cond.} (MW)	ΔT _m (K)
M-W	374.5	338	16.71	16.32	36.5
T-X	379.8	321.5	7.12	18.55	58.3
E-E	281	261	0.229	0.224	20

2. TAHP Average pressure: In the thermoacoustic devices, power density is proportional to the average pressure p_m (Swift, 1988). To maintain high power density, p_m needs to be chosen as high as possible which is set by the mechanical strength of the resonator. However, thermal penetration (δ_k) is inversely proportional to the square root of the frequency. It is known that δ_k refers to a stack of very small plate spacing, which makes the construction difficult. Considering these two effects by taking into account the preliminary choice of helium as the working medium, p_m can be a maximum 12 bar. So, $p_m = 10$ bar is chosen.
3. The next step was to set the operating frequency which has parallel dependency to the power density and thermal penetration (δ_k) as pressure has. $f = 400\text{Hz}$ is chosen to make a comparison between these two effects and the fact that the speaker resonance has to be equal to the resonator resonance in order to obtain a high efficiency of the driver.

$$\omega = 2 \times \pi \times f \quad (4.1)$$

$$\delta_K = \sqrt{\frac{2 \times K}{\rho_m \times C_p \times \omega}} \quad (4.2)$$

4. TAHP Dynamic Pressure: Swift (1988) states that as to avoid non-linear effects, for cases Mach number has to be limited to $M \approx 0.1$ which is given by following equation;

$$M = \frac{p_o}{\rho_m \times a^2} \quad (4.3)$$

Based on numerous experimental studies when $M \approx 0.1$, the drive ratio is found to be 0.02. In the first step the average pressure was chosen to be 10 bar. By placing the average pressure and drive ratio into following equation, the dynamic pressure is found to be 0.2 bar.

$$D = \frac{p_o}{p_m} \quad (4.4)$$

5. TAHP Working gas: It was explained in Section 2.4.1 that Helium proves to be the best choice of working gas due to its high velocity and thermal conductivity.
6. TAHP Normalized temperature difference (ΔT_{mn}): Having different cooling medium temperatures across the cases, there will be three different ΔT_{mn} . These are provided in Table 4.2, which is given by following equation:

$$\Delta T_{mn} = \frac{\Delta T}{T_H} \quad (4.5)$$

Table 4.2 Normalized temperature difference of the distillation columns ($\Delta T_{min}=2^{\circ}C$)

Case Identifier	T_H (K)	T_C (K)	ΔT_m (K)	ΔT_{mn} (K)
Water – Methanol	376.5	336	40.5	0.108
Toluene – Xylene	381.8	319.5	62.3	0.163
Ethylene – Ethane	283	259	24	0.085

7. TAHP Working medium parameters; For the known reboiler and condenser temperatures, working parameters of Helium are set for each of the cases, which are shown below in Table 4.3, Table 4.4 and Table 4.5.

Table 4.3 List of working fluid (Helium) parameters for the M-W distillation

Sound Velocity	$\alpha=1145$ m/s
Prandtl number	$\sigma(\text{Pr})=0.698$
Ratio of C_p to C_v	$\gamma=1.666$
Gas Density	$\rho_m=1.28$ kg/m ³
Thermal Conductivity	$K=0.183$ W/m.k
Heat capacity	$c_p=5193$ J/kg.K
Dynamic viscosity	$\mu=2.242 \times 10^{-5}$ kg/m.s

Table 4.4 List of working fluid (Helium) parameters for the T-X distillation

Sound Velocity	$\alpha=1107$ m/s
Prandtl number	$\sigma(\text{Pr})=0.697$
Ratio of C_p to C_v	$\gamma=1.666$
Gas Density	$\rho_m=1.36$ kg/m ³
Thermal Conductivity	$K=0.175$ W/m.k
Heat capacity	$c_p=5193$ J/kg.K
Dynamic viscosity	$\mu=2.2219 \times 10^{-5}$ kg/m.s

Table 4.5 List of working fluid (Helium) parameters for the E-E distillation

Sound Velocity	$\alpha=973$ m/s
Prandtl number	$\sigma(\text{Pr})=0.682$
Ratio of C_p to C_v	$\gamma=1.665$
Gas Density	$\rho_m=1.77$ kg/m ³
Thermal Conductivity	$K=0.146$ W/m.k
Heat capacity	$c_p=5193$ J/kg.K
Dynamic viscosity	$\mu=1.8523 \times 10^{-5}$ kg/m.s

8. For the selected working parameters, thermal and viscous penetration depth can be determined, shown in Table 4.6, from the following equations.

$$\delta_K = \sqrt{\frac{2 \cdot K}{\rho_m \cdot c_p \cdot \omega}} \quad (4.6)$$

$$\delta_V = \sqrt{\frac{2 \cdot \mu}{\rho_m \cdot \omega}} \quad (4.7)$$

Where

$$\omega = 2 \cdot \pi \cdot f \quad (4.8)$$

Table 4.6 The obtained thermal penetration depth and viscous penetration depth by solving the equations

Case Identifier	δ_K (mm)	δ_V (mm)
Water – Methanol	0.15	0.12
Toluene – Xylene	0.14	0.11
Ethylene – Ethane	0.112	0.096

9. Figure 4.1 shows that the selected stack geometry has a maximum COP at 1.1 for $r_h = y_0$ where r_h is hydraulic radius of stack and y_0 is position in y direction. It is suggested by Tijani (2001) that the best stack placing is $2y_0$ which is equal to 0.22mm. Wheatley, Hofler et al. (1985) proposed that in order to not to maintain the acoustic field, a spacing of $2\delta_K$ to $4\delta_K$ should be used. Therefore, $2y_0 = 0.3mm$ was chosen.
10. To define the three remaining parameters, normalized center position (X_n), normalized stack length (L_{sn}) and the cross sectional area (A), optimization of the stack has to be carried out. Tijani (2001) explains optimization of the stack for similar working parameters as in this project. A normalized stack position was used of a $x_n = 0.22$ and normalized stack length of $L_{sn} = 0.22$. shown below in Figure 4.1

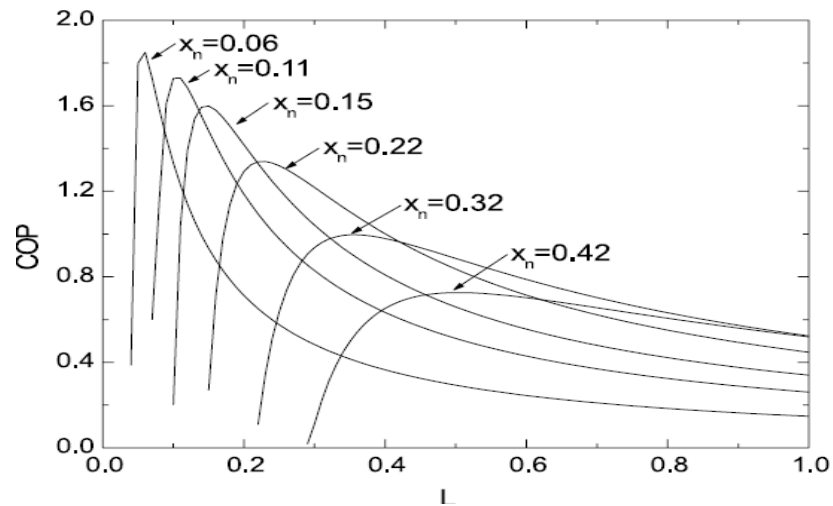


Figure 4.1 Performance calculations for the stack, as function of the L_{sn} and x_n
(Tijani, 2001)

11. By using dimensionless parameters of the working medium, the expressions (3.1) and (3.2), given in section 3.2, the heat flow and acoustic power can be determined (Tijani, 2001).
12. Under the defined conditions, the dimensionless cooling power Q_{cn} and dimensionless acoustic power W_n was found as presented in Table 4.7;

Table 4.7 Normalized thermal penetration depth, Λ and dimensionless cooling and acoustic power for the distillation columns

Case Identifier	δ_{kn}	Λ	$W_n (10^{-6})$	$Q_{cn} (10^{-6})$
Water – Methanol	0.493	0.673	3.17	6.19
Toluene – Xylene	0.468	0.686	2.74	5.07
Ethylene – Ethane	0.375	0.738	2.47	4.93

13. The relationship between dimensionless heat flow with heat flow and dimensionless acoustic power with acoustic power are given as;

$$Q_{cn} = \frac{\dot{Q}_c}{p_m \alpha A} \quad (4.9)$$

and

$$W_n = \frac{\dot{W}}{p_m \alpha A} \quad (4.10)$$

For the known cooling requirement, the stack was designed. By solving equation (4.9) the required area was defined and by replacing the required area into equation (4.10) the necessary acoustic power was determined as presented in Table 4.8. Therefore, by considering a cylindrical resonator the equivalent radius for each of the cases was defined as also shown in Table 4.8.

Table 4.8 Acoustic power demand and area requirement for the application of TAHP model to the distillation columns

Case Identifier	Q_{Reb.} (10⁴ kW)	Q_{Cond.} (10⁴ kW)	Area (m²)	Radius (m)	Acoustic work (MW)
Water – Methanol	16.71	16.32	2302	27.1	8.34
Toluene – Xylene	7.12	18.55	3304	32.4	10.00
Ethylene – Ethane	0.229	0.224	466	12.1	1.12

From the TAHP model, the required acoustic power was obtained. Then, by applying the acoustic power to a transducer, the required amount of electrical power could be found. A transducer is an apparatus that transform the electrical power to acoustic power and vice versa. The desired transformation is 100 %, however, there is no transducer that works at perfect efficiency. For this conclusion, in order to define how much electrical power is needed to obtain the required acoustic power, it is necessary to know the efficiency of transducer (η). Assuming η is 70% (Johannesson and Mitson, 1983), and the required acoustic power as shown above on Table 4.8, then the electrical power for the base cases could be calculated by applying equation (4.11);

$$Electrical\ power = \frac{Acoustic\ power}{Efficiency} \quad (4.11)$$

Table 4.9 shown below is the electrical and acoustic power requirement of the TAHP, required to remove heat from the column condenser and reject heat to the column reboiler.

Table 4.9 Acoustic power and electrical power demand for the application of TAHP model to the distillation columns

Case Identifier	Acoustic Power input (MW)	Electrical Power input (MW)
Water – Methanol	8.34	11.9
Toluene – Xylene	9.95	14.2
Ethylene – Ethane	1.12	1.6

4.1.1. Effect of Different Minimum Approach Temperatures on TAHP model Power Demand

In order to evaluate the performance of TAHP for different approach temperatures, same calculations were carried out for different minimum approach temperatures from 2°C to 10°C. The results obtained from the TAHP dimensionless model, dimensionless heat flow and dimensionless acoustic power are shown below in Table 4.10, Table 4.11, Table 4.12 and Table 4.13. Calculated required area of TAHP and electrical power demand for the application of TAHP to the base cases are also shown in Table 4.10 to Table 4.13.

Table 4.10 Power demand and area requirement of the application of TAHP model to the distillation columns at $\Delta T_{min}=2^{\circ}C$

Case Identifier	Q_{cn} (10^{-6})	W_n (10^{-6})	Area (m^2)	Radius (m)	Acoustic Power (MW)	Electrical Power (MW)
Water – Methanol	6.19	3.17	2302	27.1	8.34	11.9
Toluene – Xylene	5.07	2.74	3304	32.4	10.00	14.2
Ethylene – Ethane	4.93	2.47	466	12.1	1.12	1.6

Table 4.11 Power demand and area requirement of the application of TAHP model to the distillation columns at $\Delta T_{min} = 5^{\circ}C$

Case Identifier	Q_{cn} (10^{-6})	W_n (10^{-6})	Area (m^2)	Radius (m)	Acoustic Power (MW)	Electrical Power (MW)
Water – Methanol	5.95	3.08	2392	27.6	8.46	12.08
Toluene – Xylene	4.86	2.67	3445	33.1	10.20	14.6
Ethylene – Ethane	4.71	2.41	487	12.5	1.14	1.63

Table 4.12 Power demand and area requirement of the application of TAHP model to the distillation columns at $\Delta T_{min} = 8^{\circ}C$

Case Identifier	Q_{cn} (10^{-6})	W_n (10^{-6})	Area (m^2)	Radius (m)	Acoustic Power (MW)	Electrical Power (MW)
Water – Methanol	5.73	3.01	2487	28.1	8.58	12.26
Toluene – Xylene	4.66	2.60	3595	33.8	10.40	14.85
Ethylene – Ethane	4.50	2.33	510	12.7	1.16	1.66

Table 4.13 Power demand and area requirement of the application of TAHP model to the distillation columns at $\Delta T_{min} = 10^{\circ}C$

Case Identifier	Q_{cn} (10^{-6})	W_n (10^{-6})	Area (m^2)	Radius (m)	Acoustic Power (MW)	Electrical Power (MW)
Water – Methanol	5.58	2.96	2554	28.5	8.67	12.38
Toluene – Xylene	4.53	2.56	3702	34.3	10.50	15.00
Ethylene – Ethane	4.36	2.29	527	12.9	1.17	1.67

In Section 4.1.1 effect of different minimum approach temperatures on TAHP model power demand has been studied. It can be seen from the results that increasing or decreasing minimum approach temperature does not have a significant effect on power demand and area requirement of the application of TAHP model to the distillation base cases. Increasing minimum approach temperature two times increases power demand of the application of TAHP model to bases about 1%, and also increases the area requirement by 2%.

4.1.2. Effect of Different Working pressure on TAHP Model Power Demand

In order to assess effect of working pressure on power demand and area requirement of the TAHP model, different working pressures are studied from 10 bar to 30 bar. The results obtained from the TAHP dimensionless model, area requirement, acoustic power demand and electrical power demand, are shown below in Table 4.14, Table 4.15 and Table 4.16.

Table 4.14 Power demand and area requirement of the application of TAHP model to the distillation columns at 10 Bar

Case Identifier	Area (m ²)	Acoustic Power (MW)	Electrical Power (MW)
Water – Methanol	2302	8.34	11.9
Toluene – Xylene	3304	9.95	14.2
Ethylene – Ethane	466	1.12	1.6

Table 4.15 Power demand and area requirement of the application of TAHP model to the distillation columns at 20 Bar

Case Identifier	Area (m ²)	Acoustic Power (MW)	Electrical Power (MW)
Water – Methanol	1751	8.40	12
Toluene – Xylene	2362	10.00	14.3
Ethylene – Ethane	332	1.14	1.63

Table 4.16 Power demand and area requirement of the application of TAHP model to the distillation columns at 30 Bar

Case Identifier	Area (m²)	Acoustic Power (MW)	Electrical Power (MW)
Water – Methanol	1433	8.47	12.1
Toluene – Xylene	1893	10.10	14.42
Ethylene – Ethane	272	1.15	1.64

In Section 4.1.2 effect of pressure on the TAHP model was studied. The result shows that increasing the working pressure in TAHP model, reduces area requirement significantly. On the other hand, increasing the working pressure has no significant effect on the power demand of the TAHP model. It can be seen from the result that increasing the working pressure two times increases power demand of TAHP model by 1% while reducing area requirement of TAHP model by 25%.

4.1.3. Effect of Different Working pressure on TAHP Power Demand

In order to interpret the performance of TAHP model, different working frequency is also studied from 400 Hz to 1200 Hz. The results obtained from the TAHP dimensionless model, area requirement, acoustic power demand and electrical power demand, are presented below in Table 4.17, Table 4.18 and Table 4.19.

Table 4.17 Power demand and area requirement of the application of TAHP model to the distillation columns at 400 Hz

Case Identifier	Area (m²)	Acoustic Power (MW)	Electrical Power (MW)
Water – Methanol	2302	8.34	11.9
Toluene – Xylene	3304	9.95	14.2
Ethylene – Ethane	466	1.12	1.6

Table 4.18 Power demand and area requirement of the application of TAHP model to the distillation columns at 800 Hz

Case Identifier	Area (m²)	Acoustic Power (MW)	Electrical Power (MW)
Water – Methanol	3281	8.39	11.98
Toluene – Xylene	4653	10.00	14.3
Ethylene – Ethane	671	1.14	1.63

Table 4.19 Power demand and area requirement of the application of TAHP model to the distillation columns at 1200 Hz

Case Identifier	Area (m²)	Acoustic Power (MW)	Electrical Power (MW)
Water – Methanol	4055	8.46	12.08
Toluene – Xylene	5719	10.10	14.42
Ethylene – Ethane	830	1.15	1.64

In Section 4.1.3 effect of working frequency was studied. The results obtained from the TAHP model illustrates that increasing frequency, increases area requirement of TAHP model significantly. However, increasing frequency of the system almost has no effect on the power demand of the TAHP model. It can be seen from the result that duplicating the working frequency increases the area requirement of the TAHP model by 20% while increasing power demand of the model by just 1%.

4.2.Application of CHP to Distillation Columns

To evaluate conventional heat pump alternatives, a CHP cycle was designed for each of the cases. The external cooling and heating requirement of the cases and the associated temperatures are shown below in Table 4.20.

Table 4.20 The distillation base cases condenser and reboiler duties and associated temperatures

Case identifier	Condenser		Reboiler	
	Duty (MW)	Temp. (K)	Duty (MW)	Temp. (K)
Water – Methanol	16.32	338	16.71	374.5
Toluene – Xylene	18.55	321.5	7.12	379.8
Ethylene – Ethane	0.224	261	0.229	281

By applying associated input data and placing any appropriate apparatus, the CHP cycles were designed and the required shaft work for each of cases was obtained. Table 4.21 presents the power demand for the first and second compression stages to meet the heating and cooling requirements of the columns which can be clearly seen in Figure 3.4 Figure 3.5.

Table 4.21 Vapour compression heat pump power demand to meet external cooling and heating requirement of the distillation columns

Case identifier	First Stage	Second Stage	First Stage	W _{Tot.} (MW)
	Compression W _{Comp.} (MW)	Compression W _{Comp.} (MW)	Pumping W _{Pump} (MW)	
W-M	-	3.2	0.009	3.21
T-X	-	4.7	0.35	5.05
E-E	0.37	0.025		0.40

4.3. Coefficient of Performance of Thermoacoustic Heat Pump and Conventional Heat Pump

As introduced in Section 2.4, COP is used as performance indicator for heat pumps. In order to evaluate viable and economical application of TAHP, COP calculation for TAHP and CHP is carried out by using equation (2.1), which is also stated in Section (2.4).

Table 4.22 COP of TAHP and CHP for the base cases

Case Identifier	COP _{TAHP}	COP _{CHP}
Water – Methanol	1.36	5.08
Toluene – Xylene	1.29	3.67
Ethylene – Ethane	0.14	0.56

As it is stated in Section 2.4, COP is used as a performance indicator for heat pumps. Therefore, in order to evaluate performance of TAHP, in Section 4.3 coefficient of performance (COP) was studied. It can be easily seen in Table 4.22 that COP of compression heat pump is higher than the COP of TAHP model about 3 to 4 times. It can be stated here that compression heat pump is more efficient than the TAHP model.

4.4. Operating Cost Calculation of TAHP, CHP and External Utilities

Table 21 shown below the typical cost of three different steam levels (HP, MP and LP) and the industrial electricity cost. Cost calculations for the external utilities are shown in Appendix B.

Table 4.23 Price of HP, MP, LP and Industrial Electricity

Steam Level	HP (40 Bar, 400 °C)	MP (20 Bar, 300 °C)	LP (2 Bar, 120 °C)
Cost (£/t)	18.4	16.0	12.2
Cost (£/ GJ)	8.64	7.56	5.73
Electricity Cost (£/kW.h)	0.07		

The cooling and heating needs of the selected distillation columns are shown in Table 4.24. TAHP and CHP power demand is also presented in Table 4.24.

Table 4.24 Heating and cooling requirements of the distillation columns, and power demand of the application of TAHP and CHP to the distillation base cases

Case identifier	Q_{Reb.} (MW)	Q_{Cond.} (MW)	TAHP Electrical Power Demand (MW)	CHP Electrical Power Demand (MW)
Water – Methanol	16.71	16.32	11.85	3.21
Toluene – Xylene	7.12	18.55	14.22	5.05
Ethylene – Ethane	0.229	0.224	1.6	0.40

By carrying out the related cost calculation, the annual operating costs of the three distillation columns are found as in Table 23.

Table 4.25 Annual operating costs of TAHP, CHP and External utilities in order to satisfy the distillation columns

Case identifier	TAHP (10⁶ £/y)	CHP (10⁶ £/y)	External Utilities LP+CW (10⁶ £/y)
Water – Methanol	7.13	1.93	3.47
Toluene – Xylene	8.56	3.04	1.55
Ethylene – Ethane	0.96	0.24	-

4.5. Discussion of Results

The aim of this dissertation was to study the implementation of TAHP model in distillation columns. A literature review was performed on heat pumps by focusing on the application of TAHP model. To achieve the aims of the dissertation, first a TAHP model was identified and the model was applied to supply heating and cooling to the distillation columns. In order to carry out a critical evaluation of TAHP model, compression heat pump was applied to the selected distillation columns and the associated power demand for the application of compression heat pump was identified. Also, for the above ambient distillation columns, external utility cost calculations were carried out.

Chapter 4 details the application of the TAHP model and compression heat pump to the base cases. Table 4.24 provides the heating and cooling needs of the distillation columns and power demand for the application of TAHP and compression heat pump. The associated annual operating costs of the TAHP, compression heat pump and external utilities are presented in Table 4.25.

First of all, the performance evaluation of TAHP model was carried out by changing the working parameters of the TAHP model such as, working pressure, minimum approach temperature and working frequency. The results obtained from the model shows that minimum approach temperature has no significant effect on the power demand and the area requirement of the TAHP model. Increasing the minimum approach temperature increases the power demand and the area requirement of the TAHP model by 1 to 2 %.

On the other hand working pressure has significant effect on the area requirement. The results demonstrate that duplicating the working pressure reduces area requirement of the TAHP model by 25 % while it almost has no effect on power demand of the model. Additionally, the working frequency was studied. The results obtained from the TAHP model shows that increasing working frequency increase area requirement of the model while it has no significant effect on power demand of the TAHP model.

Application of a heat pump below ambient temperature is necessary to operate a distillation column. Therefore, compression heat pump and TAHP models have been introduced for an Ethylene - Ethane sub-ambient distillation column. Power demand of TAHP application to Ethylene - Ethane separation is defined to be about four times higher than power demand of CHP.

The results obtained from the application of both models points out that the application of TAHP does not bring about any benefits in terms of energy saving. In addition to high power demand, the high area demand of the TAHP is another weakness of the application of TAHP to Ethylene - Ethane separation.

TAHP and compression heat pump were also applied to above ambient temperature distillation columns for Toluene - Xylene and Water - Methanol separations. It is observed from the results that power the demand of TAHP is about three times higher than power demand of compression heat pump. The results obtained from the simulation of compression heat pump and TAHP models states that the application of the TAHP to above ambient temperature distillation columns, also, does not bring any associated benefits.

In order to assess the compression heat pump and TAHP model at above ambient temperatures, external utilities (Low pressure steam and cooling water) were applied to satisfy the cooling and heating requirements of the Toluene - Xylene and Water - Methanol. The annual operating cost results are presented in Table 4.25. The results of the implementation of the external utilities suggest that when the temperature difference between the reboiler and condenser is small and heating needs of the column is high; using a heat pump could prove beneficial. On the other hand, when the temperature difference over the column is small, the heating needs of the column are small and LP steam is satisfactory, using a heat pump does not bring about any benefits.

In conclusion, a statement can be carried out that a heat pump could prove beneficial in terms of energy saving while the temperature difference over the column is low and the amount of heat that needs to be upgraded is high enough as it is suggested by Annakou and Mizsey (1995). However, when the temperature difference over the column is high and low pressure steam is satisfactory, using a heat pump does not bring about any benefits in terms of energy saving.

5. Conclusions and Recommendation for Future Research

5.1. Conclusions

In this final chapter the results and discussion as presented in Section 4.5 will be summarized. Suggestions for improvements to the work performed in this dissertation are made, as well as recommendations for the direction of future research.

The published TAHP reports and designed TAHP devices by various researchers assert that this technology is promising for energy savings in distillation (Bruinsma and Tijani, 2005; Bruinsma, 2010; Vanapalli, Tijani et al., 2010). It was expected that the results of this dissertation would show that the TAHP model is superior to the traditional heat pump technologies in terms of reducing energy demand of distillation columns. However, the observation from the results suggests that the power demand of TAHP model is quite high relative to that of compression heat pump. The result obtained from the simulation of compression heat pump and the application of TAHP model to the base cases shows that use of TAHP model requires 3 to 4 times more electrical power in order to operate, which can be seen from the results in Table 4.24.

The dimensionless TAHP model, which has been conducted in this dissertation, has been applied on different cases which focus on small duties from 1-100 W, and the reports they have been published proposes that when the temperature of heat source is 10°C and temperature of heat sink temperature is 80°C , the COP of the TAHP model is about 2.5 (Tijani, 2001; Bruinsma and Tijani, 2005). However, in this dissertation the COP of TAHP model of the selected distillation base cases, which have different range of temperatures from below ambient to above ambient temperature, was found to be about 1.36, 1.29 and 0.14 while the COP of compression heat pump was found to be about 3 to 4 times higher than the COP of TAHP model. Tijani (2001) and Bruinsma and Tijani (2005) suggest that the TAHP model can be used in separation industry. However, the results shows that the TAHP model does not bring any benefits in terms of energy saving.

The published papers by the ECN (Energy Research Centre of the Netherlands) also suggest that the TAHP model could prove beneficial in terms of energy saving (Vanapalli, Tijani et al., 2010; Tijani and Spoelstra, 2012). However, the published papers focus above ambient temperatures from 10-80°C and also small heating and cooling requirements from 1 - 100 W. They have not been analysed any below ambient distillation column and high heating and cooling requirement. Therefore, as the results of this dissertation shows that, the assertion they have made, the TAHP model can be applied to distillation column, is not valid.

5.2.Recommendations for Future Research

The published TAHP reports are encouraging, however, when it comes to practicality much research and improvements still needs to be done to reach viable and economical large scale applications.

Two types of heat pumps have been reviewed, and it is found out that the relative performance of TAHP is 3 to 4 times less than conventional heat pump. For a better understanding of the relative performance of TAHP, more experimental and computational work is needed which are mainly focus on reducing thermal and acoustical losses.

As introduced before in section 5, TAHP reports focus on small heating and cooling duties. Therefore, up scaling is needed for a better comparison of TAHP with conventional heat pumps. A better evaluation of TAHP may be achieved by taking into account in parallel a wider range of parameters, such as porosity, geometry, physical properties of working medium and the material being used.

Although conversion efficiency of electrical power to acoustical power is about 70 %, in principle, in order of realizable and efficient conversion, electroacoustic conversion is also another important issue that needs to be searched.

As it is discussed in Section 4.5, the working pressure and the working frequency has greatest influence on performance of the TAHP model. For this dissertation, the optimum working pressure and working frequency was chosen based on the material and working fluid. If further improvement can be made on the material and working fluid that is used in TAHP model, the performance of the TAHP model can be improved. Therefore, a research needs to be carried out by focusing on working pressure and working frequency of the TAHP model.

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Appendix A

Automated Dimensionless TAHP Model on Excel

Involved Temperatures			
$T_{\text{Reb.}}$	376.5	K	
$T_{\text{Cond.}}$	336	K	
ΔT_m	40.5	K	
$Q_{\text{Cond.}}$	1.63E+07	W	
Average Pressure			
P_m	1.00E+06	N.m/s	
Frequency			
f	400	Hz	
Dynamic Pressure			
P_o	0.2	Bar	
Drive Ratio			
D	0.02		
Working Gas (Helium Properties)			
Velocity	α	1145	m/s
Prandtl Number	σ	0.698	
Ratio of C_p to C_v	γ	1.666	
Gas Density	ρ_m	1.28	kg/m ³
Thermal Conductivity	K	0.183	W/m.K
Heat Capacity	C_p	5.19E+03	J/kg.K
Dynamic Viscosity	μ	2.24E-05	kg/m.s
Normalized Temperature Difference			
ΔT_{mn}	0.10756972	K	
Angular Frequency			
ω	2513.27412		
Thermal penetration Depth			
δ_K	0.15	mm	
Viscous penetration Depth			
δ_v	0.12	mm	
Normalized stack position			

X_n	0.22	
Stack Placing		
y_0	0.3	mm
Normalized stack length		
L_{sn}	0.22	
Normalized thermal penetration Depth		
δ_{kn}	0.49338417	
Λ	0.67275167	
Porosity	0.75	
Normalized Heat Flow		
Q_{cn}	6.1899E-06	
Area		
A	2302.65	m^2
Radius		
r	27.0731599	m
Normalized Acoustic Power		
W_n	-3.165E-06	
Acoustic Power		
W	8.34E+06	W

Appendix B

Hot utility Cost Calculation

A hot utility energy cost calculation method is proposed by Sinnott and Towler (2009), shown below. The equation is used to calculate cost of external heating requirement of the distillation columns.

$$P_{HPS} = P_F \times \frac{dH_b}{\mu_B} + P_{BFW}$$

A boiler is used to produce 40 bar HP steam and steam turbine is used to reduce pressure of the steam to MP and LP level. Table B.2 is also presented to show the assumptions that are stated to calculate steam and cooling water cost.

Table B.1 Steam levels and physical properties

Steam Level	HP	MP	LP
Pressure (Bar)	40	20	2
Superheated Temperature (°C)	400	300	120.2
Saturation Temperature (°C)	250	212	120.2
Superheated Enthalpy (kJ/kg)	3214	3025	2707
Specific Enthalpy, hg, (kJ/kg)	2801	2800	2707
Specific Enthalpy, hf, (kJ/kg)	1085	898	504

Table B.2 Stated Assumptions to calculate steam cost

Furnace efficiency	0.85
Steam Turbine Efficiency	0.85
Electricity cost (£/kW.h)	0.07
Fuel Cost (Carpenter, 2013) (£/Gj)	7.45
Company will run (h/y)	8600
The boiler feed water cost is cancelled by a condensate credit.	

The shaft-work produced by steam turbine while reducing the level of the steam to desired level will be calculated and subtracted from steam price to find out real steam price.

Isentropic enthalpy difference between steam levels

Isentropic delta enthalpy (kJ/kg)	189	318
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Multiplying the isentropic enthalpy difference by the turbine efficiency, non-isentropic enthalpy can be defined.

Non-isentropic delta enthalpy (kJ/kg)	151.2	254.4
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Non-isentropic delta enthalpy can be converted to the shaft-work

Shaft work (kWh/t)	18.9	31.8
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By multiplying shaft work with the electricity cost, shaft work credit can be defined.

Shaft work credit (£/t)	2.27	3.82
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$$P_{HPS} = 7.45 \frac{\text{£}}{\text{Gj}} * \frac{2.1 \text{ Gj/t}}{0.85}$$

$$P_{HPS} = 18.4 \frac{\text{£}}{\text{t}}$$

By subtracting defined shaft work credit the real steam price can be found.

Steam Level	HP	MP	LP
Cost (£/t)	18.4	16.1	12.2

Cold Utility Cost Calculation

A cooling water cost calculation method is suggested by Smith (2005) shown below. The equation is used to calculate cost of the external cooling requirement of the distillation columns.

$$P_{CW} = QC_{min} \times P_E \times \frac{0.01}{3600}$$

Water - Methanol Separation External Utility Cost Calculation

LP Steam

$$LP_{Cost} = \frac{16.71 \text{ MW}}{(2707 - 504) \frac{\text{kJ}}{\text{kg}}} \times \frac{10^3 \frac{\text{kJ}}{\text{s}}}{\text{MW}} \times \frac{1}{0.85} \times 12.2 \frac{\text{£}}{\text{t}} \times \frac{\text{t}}{1000 \text{ kg}} \times (8600 \times 3600) \frac{\text{s}}{\text{y}}$$

$$LP_{Cost} = 3.37 \times 10^6 \frac{\text{£}}{\text{y}}$$

Cooling Water

$$CW_{Cost} = 16.32 \times 10^3 \text{ kW} \times 0.07 \frac{\text{£}}{\text{kW} \cdot \text{h}} \times 0.01 \times 8600 \frac{\text{h}}{\text{y}}$$

$$CW_{Cost} = 0.098 \times 10^6 \frac{\text{£}}{\text{y}}$$

Toluene - Xylene Separation External Utility Cost Calculation

LP Steam

$$LP_{Cost} = \frac{7.12 \text{ MW}}{(2707 - 504) \frac{\text{kJ}}{\text{kg}}} \times \frac{10^3 \frac{\text{kJ}}{\text{s}}}{\text{MW}} \times \frac{1}{0.85} \times 12.2 \frac{\text{£}}{\text{t}} \times \frac{\text{t}}{1000 \text{ kg}} \times (8600 \times 3600) \frac{\text{s}}{\text{y}}$$

$$LP_{Cost} = 1.44 \times 10^6 \frac{\text{£}}{\text{y}}$$

Cooling Water

$$CW_{Cost} = 18.55 \times 10^3 \text{ kW} \times 0.07 \frac{\text{£}}{\text{kW} \cdot \text{h}} \times 0.01 \times 8600 \frac{\text{h}}{\text{y}}$$

$$CW_{Cost} = 0.11 \times 10^6 \frac{\text{£}}{\text{y}}$$