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Optimal design of multicomponent VOC condensation systems

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Abstract

The objective of this work is to address the problem of optimally selecting and designing condensation systems for the recovery of volatile organic compounds (VOCs) from gaseous emissions. In a typical VOC condensation system, numerous refrigerants may be technically feasible for achieving the desired VOC recovery. The task of selecting the most economical refrigeration system is a challenging one. All potentially applicable refrigerants ought to be simultaneously screened so as to select the best separation system. Such an optimal system may be a hybrid process which includes more than one refrigeration unit. This paper presents a systematic design technique for optimizing the selection of refrigeration systems for gaseous emissions with multiple VOCs. The technique developed involves a three-stage targeting approach. The first stage identifies a VOC condensation network which possesses the minimum annual operating cost. The second stage involves the minimization of the fixed cost of the refrigeration units so as to achieve the minimum operation cost determined in stage one. Stage three entails the determination of the final refrigeration network, whereby tradeoffs between operating and fixed costs are considered. A case study covering the recovery of multiple VOCs from the gaseous emission of a magnetic tape manufacturing plant will be solved using the design methodology.

1. Introduction

Several regulations have been recently enacted to limit the discharge of volatile organic compounds (VOCs) to the environment. For instance, Title I of the Clean Air Act Amendments of 1990 calls for a reduction of VOC emissions in areas that exceed the current national ambient air quality standard for ozone of 0.12 ppm. Additionally, VOCs have also been regulated under Title III of the Amendments, which requires a reduction of the emission of 189 hazardous air pollutants, many of which are VOCs.

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Due to the significant economic implications of VOC environmental regulations on chemical process industries, much attention has been recently directed towards developing techniques for selecting and designing VOC-removal systems (e.g. [1,2]).

There are several techniques for recovering VOCs from gaseous wastes. In particular, three separation technologies have been commonly used in industry; adsorption, absorption, and condensation. The first two technologies belong to a class of problems known as mass-exchange networks (MENs). The main task in designing a MEN is to transfer certain pollutants (e.g., VOCs) from a number of waste streams to a number of mass-separating agents (e.g., adsorbents, solvents, etc.) using direct-contact mass exchangers (e.g. adsorbers, absorption columns, etc.). Several techniques have been developed for the optimal design of MENs [3–6]. On the other hand, much less attention has been given to the design of VOC-recovery systems via condensation. A VOC-condensation system consists of three essential sections: dehumidification, heat integration, and VOC condensation (Fig. 1). The objective of dehumidification is to cool the gaseous waste to a temperature that is slightly above the freezing temperature of water. Hence, almost all the water vapor in the gaseous waste is condensed. This step is conducted to prevent the detrimental icing effects that take place when the gas is cooled to temperatures below 273 K in the VOC condensation section [7]. The objective of the heat integration section is to economically maximize the amount of cooling achieved by matching the “hot” gaseous emission stream with the “cold” portion of this stream after the VOC has been condensed. Owing to the stringent environmental regulations imposed on the emission of VOCs, the gaseous wastes must be cooled to very low temperatures so as to condense the VOCs to the required level. These low temperatures necessitate the use of refrigeration systems.

The challenging task of designing a VOC condensation system stems from several considerations. The designer has to simultaneously screen several refrigerants and select those which minimize the total annualized cost of the network. This problem is further compounded by the fact that many of the industrial refrigerants (CFCs) are being replaced by a new generation of refrigerants. Hence, in light of the paucity of performance criteria for these emerging refrigerants, the objective of developing a systematic procedure for screening refrigerants is a timely issue. In addition to selecting refrigerants, the designer also has to identify their optimal flow rates so as to tradeoff fixed versus operating costs. Furthermore, one should determine the optimum sequence of units and system configuration. Owing to the prohibitively enormous number of design alternatives, any approach which is based on enumerating several options and comparing them is prone to failure. Indeed, what is needed is a systematic methodology for tackling the problem.

In this work, we develop a systematic procedure for the optimal design of VOC-recovery systems in which separation is accomplished by means of condensation. In particular, the proposed procedure provides answers to the following decision-making questions:

- Which refrigerants ought to be used for cooling/condensation?
- What is the optimal load to be removed by each refrigerant?

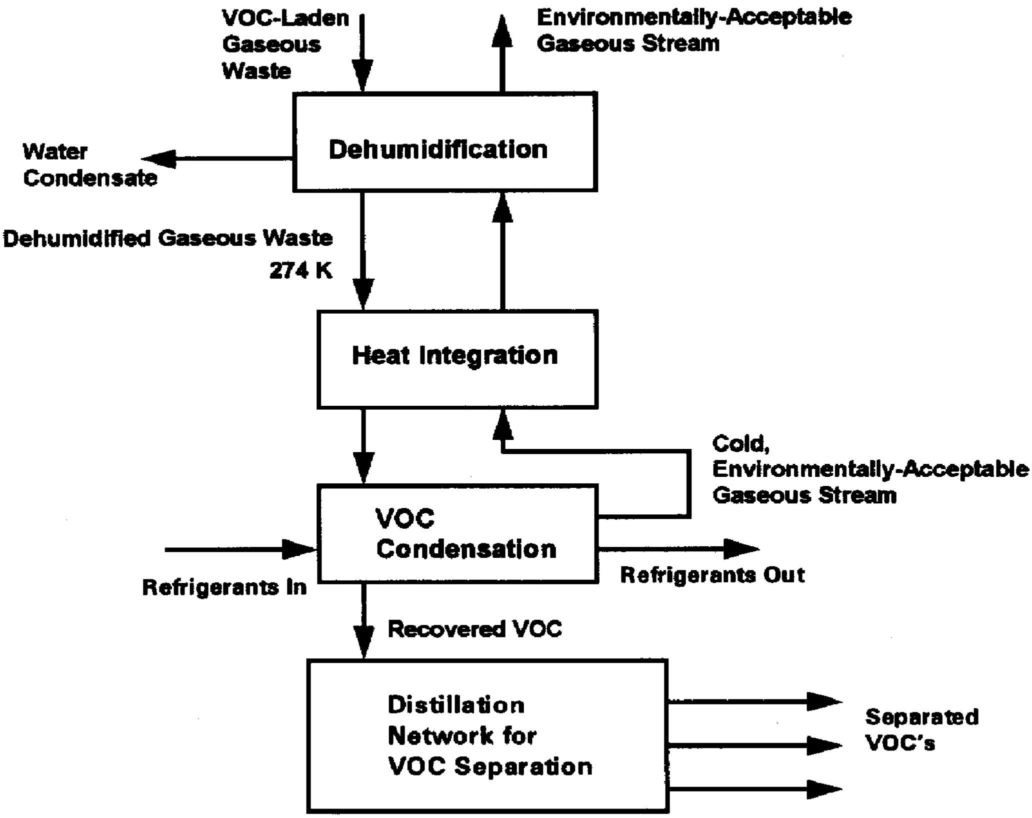

Fig. 1. A schematic representation of the VOC condensation/distillation network.

- What is the sequence of waste stream/refrigerant matches and how should the system be configured?

The problem dimensionality will be reduced to a manageable size by adopting a three-stage targeting approach. In the first stage, the minimum energy cost needed to affect the separation task is determined. In the second stage, a network is generated to feature the minimum number of coolers/condensers that require the minimum energy cost. Finally, in the third stage, operating cost is traded versus fixed cost with the objective of minimizing the total annualized cost of the system. A case study is solved to elucidate the merits of the proposed design procedure.

2. Problem statement

Consider a gaseous waste stream whose flow rate is G, temperature is T^s and contains a number N_V of VOCs. The composition of the ith VOC is y_i^s, where i corresponds to each VOC in the emission and $i = 1, 2, \ldots, N_V$. The design task is to synthesize a cost-effective network of refrigeration units which can reduce the VOC compositions to an environmentally acceptable level through condensation. Available for service are a number NE of refrigerants. The nth refrigerant (where

$n = 1, 2, \ldots, \mathrm{NE}$) can reduce the temperature of the waste stream to T_n. For convenience in presenting our design approach we will use the following terminology for the refrigerants. The index n increases in the same order as T_n, i.e.

$$T_1 \leq T_2 \leq \ldots T_n \ldots \leq T_{\mathrm{NE}}. \tag{1}$$

The flow rate of each refrigerant is unknown and is to be determined via optimization. The unit operating cost of the nth refrigerant (referred to as CH_n, \$/kJ removed) is calculated based on the equations presented in Appendix A.

3. Selection of a target temperature

Prior to developing the design approach needed to solve this problem, it is necessary to identify the target composition of the VOCs, y_i^t, where $i = 1, 2, \ldots, N_V$. Since separation is accomplished via condensation, the degree of VOC recovery is strictly linked to the target temperature, T^t, to which the gaseous waste should be cooled. Two cases exist with regard to the extent of recovering multicomponent VOCs. These cases are specified below.

3.1. Case 1: Recovery efficiency for each VOC is specified

Case 1 corresponds to the design task where a specified recovery fraction of each VOC, η_i, is desired. For this case, one must determine the target mole fraction of each VOC based on the following equation:

$$y_i^t = (1 - \eta_i) y_i^s, \qquad i = 1, 2, \ldots, N_V. \tag{2}$$

The target temperatures corresponding to these compositions are then determined from the following equation:

$$y_i^t = \frac{P_i^0(T_i^t)}{P}, \tag{3}$$

where $P_i^0(T_i^t)$ is the vapor pressure of the ith VOC at temperature T_i^t. The ultimate target temperature for the gaseous stream corresponds to the lowest target temperature calculated for the individual VOCs. This case is equivalent to cooling the stream to a temperature that is dictated by the separation of the VOC that is most difficult to recover. Hence, the condensation system may accomplish degrees of recovering a number of VOCs that are greater than the specified extents of recovery.

3.2. Case 2: Overall recovery efficiency of the system is specified

The second case corresponds to the design task whereby a certain overall recovery fraction, η, of the VOCs is required regardless of the recovery fractions of the individual VOCs. For this case, a cumulative inlet composition of the VOCs can be determined by

$$y^s = \sum_{i=1}^{N_V} y_i^s. \tag{4}$$

The overall target composition based on the desired recovery efficiency is then determined by

$$y^t = (1 - \eta)\cdot y^s \tag{5}$$

and the target temperature corresponding to this overall composition is determined from the following equation:

$$y^t = \sum_{i=1}^{N_V} \frac{P_i^0(T^t)}{P}. \tag{6}$$

In either case 1 or 2, the VOC-recovery task can now be expressed in terms of cooling the gaseous waste to a target temperature, T^t. In the sequel we develop a procedure for designing an optimal refrigeration system which is capable of cooling the gaseous emission to its target temperature.

4. Design approach

A complete design of the VOC-recovery system entails the identification of refrigerants to be employed, their flow rates, system configuration and unit design. In the following, we develop a three-stage targeting approach which generates a cost-effective VOC-recovery system. In the first stage, the minimum operating cost of the system is identified. This target seeks to minimize the operating (utility) cost of the network. In the second stage, we synthesize a network which features the minimum number of condensers that realizes the minimum operating cost of the system. This target is aimed at minimizing the fixed cost of the network since a lower number of units typically leads to lower fixed costs (e.g., the six-tenth factor rule, [8]). In the third stage, tradeoffs between the operating and fixed costs are established to determine the network that results in the minimum total annualized cost.

In the following sections we present a systematic approach to minimizing the operating cost of the network. We first introduce a new concept called the stacked-temperature diagram (STD). This system representation is conducive to identifying the minimum operating cost. Then, we develop an optimization formulation to address the problem at hand.

5. The stacked-temperature diagram (STD)

The STD is a useful tool to identify the type and flow rates of refrigerants which will yield minimum operating cost. In order to construct the STD, each waste stream is split into NE + 1 parallel portions. Each portion, n, is first matched with the NEth refrigerant followed by the NE − 1 refrigerant, and so on until it concludes by a match with the *n*th refrigerant. It is worth reminding that according to our terminology

$$T_1 \leq T_2 \ldots \leq T_n \leq \ldots T_{\mathrm{NE}-1} \leq T_{\mathrm{NE}}. \tag{1}$$

The flow rate of the *n*th portion of the waste stream, denoted by g_n, is unknown and is to be determined so as to minimize the operating cost of the system. A schematic representation of the STD is given in Fig. 2. As will be shown later this representation embeds all system configurations featuring minimum operating cost including those with stream splitting and mixing.

For the *n*th portion of the waste stream one can readily identify the optimal policy of matches with refrigerants which minimizes energy cost for that portion. This can be achieved by adopting the following simple procedure. Consider two refrigerants, *u* and *v*, that are represented on the *n*th portion of the STD such that $T_u < T_v$. If the following condition holds

$$\mathrm{CH}_u < \mathrm{CH}_v, \tag{7}$$

one can delete the match of the *v*th refrigerant with the *n*th portion of the waste stream. This procedure is dictated by the objective of minimizing energy cost. The elimination of *v* in favor of *u* is attributed to the fact that if a refrigerant at a more favorable thermodynamic quality (lower temperature) can remove the same load

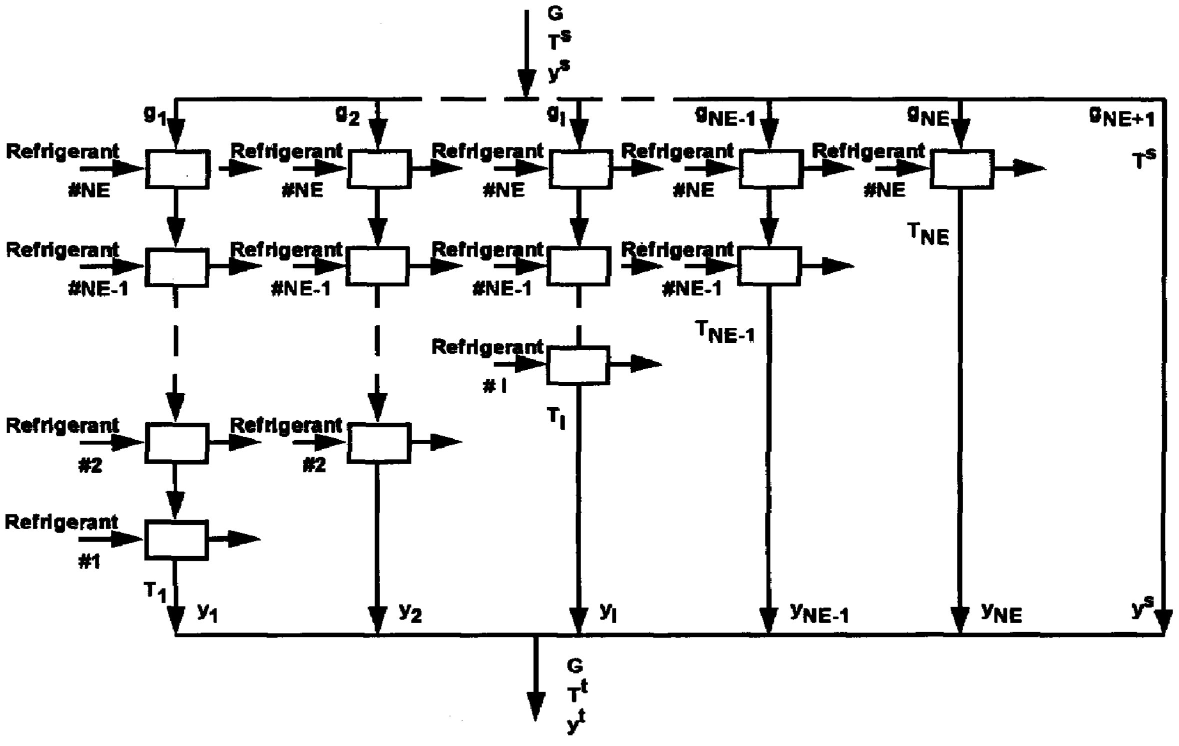

Fig. 2. A schematic representation of the STD.

handled by another refrigerant at a less favorable thermodynamic quality (higher temperature) while incurring less cost, then one should use the refrigerant with the more favorable thermodynamic quality. By applying this procedure to all portions of the waste stream, one establishes an optimal matching policy which will minimize energy (utility) cost. Hence, we use the term minimum utility stacked temperature diagram (MUSTD) to designate an STD for which all non-optimal matches have been eliminated. It is worth pointing out that the mole fractions of the VOCs in the stream leaving the nth portion of the MUSTD, $y_{n,i}$, can be calculated as follows:

$$y_{n,i} = y_i^s \quad \text{if } T_n \geq T_i^c, \tag{8a}$$

$$= \frac{P_i^0(T_n)}{P} \quad \text{if } T_n < T_i^c, \tag{8b}$$

where $P_i^0(T_n)$ is the vapor pressure of the ith VOC at a temperature T_n, P is total pressure of the gaseous waste and T_i^c is the temperature at which condensation of the ith VOC in the gaseous waste begins. T_i^c is characterized by the following equation:

$$y_i^s = \frac{P_i^0(T_i^c)}{P}. \tag{9}$$

In order to demonstrate the notion of constructing a MUSTD, consider the following illustrative example. A waste stream can be potentially matched with four refrigerants whose operating costs are arranged in an order of ascending cost ($/kJ removed) as CH_3, CH_4, CH_1, and CH_2 (with the third refrigerant having the least unit cooling cost, $/kJ, and the second refrigerant having the highest unit cooling cost $/kJ). By applying the aforementioned procedure, one can obtain the MUSTD shown in Fig. 3.

A particularly useful result of the MUSTD is the minimum utility cost for the nth portion of the waste stream expressed as $/kmol of g_n. This number will be denoted by CM_n. It can be easily calculated as follows. Consider for instance the first portion of the MUSTD in Fig. 3. The parameter CM can be calculated as follows:

$$CM_1 = CH_3(h^s - h_3) + CH_1(h_3 - h_1), \tag{10}$$

where h^s, h_3 and h_1 refer to the stream enthalpy at T^s, T_3 and T_1, respectively. A particularly useful category is encountered when we assume that the latent heat of condensing the VOC is negligible with respect to the sensible heat needed to cool the gaseous stream (a typically valid assumption for low VOC concentrations), then

$$CM_1 = Cp_1[CH_3(T^s - T_3) + CH_1(T_3 - T_1)]. \tag{11}$$

6. Formulation for minimum utility

We are now in a position to formulate the problem of minimizing the utility (energy) cost of the refrigerants. The following is an optimization formulation which seeks to

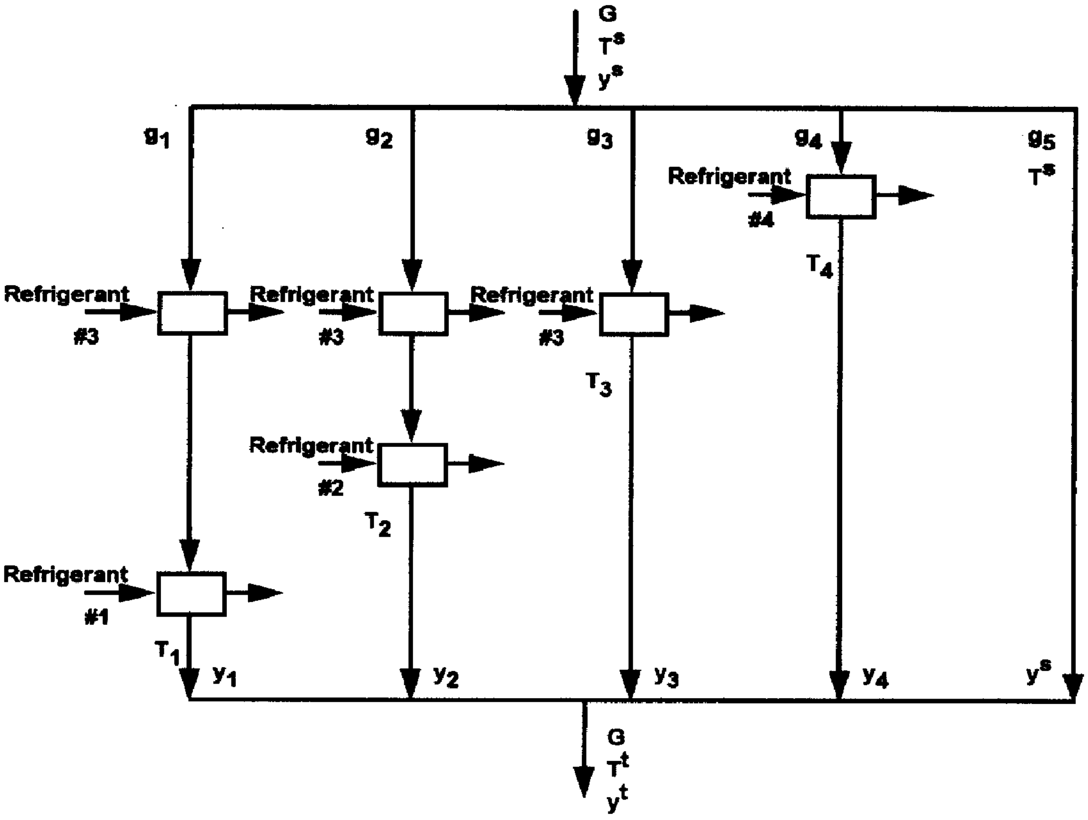

Fig. 3. A MUSTD of the illustrative example.

identify the minimum utility cost for the system. As will be shown, this program corresponds to the task of optimally distributing the flow rate G over the parallel portions $n = 1, 2, \ldots, \mathrm{NE}$ of the MUSTD.

$$\text{(P1)} \qquad \min \sum_{n=1}^{\mathrm{NE}} \mathrm{CM}_n g_n$$

$$\text{subject to } \sum_{n=1}^{\mathrm{NE}+1} g_n = G,$$

$$\sum_{n=1}^{\mathrm{NE}+1} g_n Cp_i T_n = G Cp_i T^t,$$

$$g_n \geq 0, \quad n = 1, 2, \ldots, \mathrm{NE} + 1.$$

This is a linear program whose objective function seeks to minimize the energy cost of the refrigerants needed to tackle the waste stream. The first constraint is an overall material balance which distributes G over the NE + 1 parallel portions of the MUSTD. The second constraint insures that the gaseous stream is cooled to a temperature which corresponds to the required condensation level of the VOC. The value of

T^t can be calculated via the following equation:

$$y^t = \frac{P^0(T^t)}{P}. \tag{12}$$

The third set of constraints are non-negativity constraints for the flow rate of each parallel portion of the MUSTD. The solution of this program identifies the optimal distribution of G over the NE + 1 parallel portions so as to minimize the energy cost of the system. Once the optimal g's are determined, the flow rate of each refrigerant can be calculated by conducting a heat balance around each block in the MUSTD.

7. Minimizing the number of coolers/condensers

As mentioned earlier, this target seeks to indirectly minimize the fixed cost of the network while realizing the minimum energy cost of the system that has been identified in the previous section. In the sequel, we will show that the minimum number of coolers/condensers that satisfy the minimum utility cost is equal to the number of refrigerants whose flow rates were found to be non-zeros in the problem of minimizing the energy cost of refrigerants. This can be inferred by examining the MUSTD. Although a refrigerant can operate on more than one portion of the MUSTD, each block involving that refrigerant will feature the same inlet and outlet temperatures. Hence, according to the six-tenth factor rule [8], one should merge the various blocks involving that refrigerant into a single cooler/condenser. By repeating the same procedure for each refrigerant, one can show that the minimum number of coolers/condensers that realize the minimum cost of refrigerants is indeed equal to the number of refrigerants whose flow rates did not vanish in the solution to the problem of minimizing the energy cost of refrigerants. When this merging procedure is coupled with the structure of the MUSTD, one can also identify any bypass or mixing of portions of the gaseous waste.

8. Trading off capital and fixed costs

The final target for this design procedure is the identification of the minimum annualized cost network (MACNET). This target is based on trading off the operating cost of refrigerants previously determined using the minimum utility formulation with the fixed cost of refrigeration units. Indeed, it may be possible to increase the energy requirement of one refrigerant so as to reduce the number of refrigeration units purchased. Consider a system featuring minimum energy cost in which two consecutive refrigerants, u and v, are used ($T_u > T_v$). The question addressed is whether the elimination of refrigerant u in favor of refrigerant v will result in a reduced total annualized cost of the network. This analysis requires that the increase in energy cost of refrigerant v (to provide the refrigeration load previously supplied by refrigerant u) is less than the annualized fixed cost saved by eliminating the uth refrigeration system.

This analysis is repeated for each two consecutive units, thereby resulting in a MACNET.

A final consideration made in this design methodology involves the amount of heat integration incorporated between the "hot" gaseous emission stream and the "cold" emission stream after the VOC is condensed. This involves tradeoffs between the flow rate of refrigerant required for the condensation task and the amount of heat transfer surface area needed for the cooling/condensation processes. The tradeoff between these two design criteria can be evaluated by determining the amount of heat integration that results in a minimum annualized cost of the system. In summary, MACNETs at different temperature differences across the heat integration portion of the process block diagram are determined to allow the designer to evaluate the temperature difference that results in the minimum annualized cost system.

9. Case study: VOC recovery from a gaseous emission

Fig. 4 is an overview of a magnetic tape manufacturing plant. Magnetic tape is manufactured via a coating process where a solvent mixture containing magnetic pigments, binders, dispersants, and lubricants is applied to a polyester basefilm. This basefilm containing VOCs is then dried in a multiple-zone oven. The gaseous emission stream exits the coating line dryer. The multiple coating lines emit a total gaseous

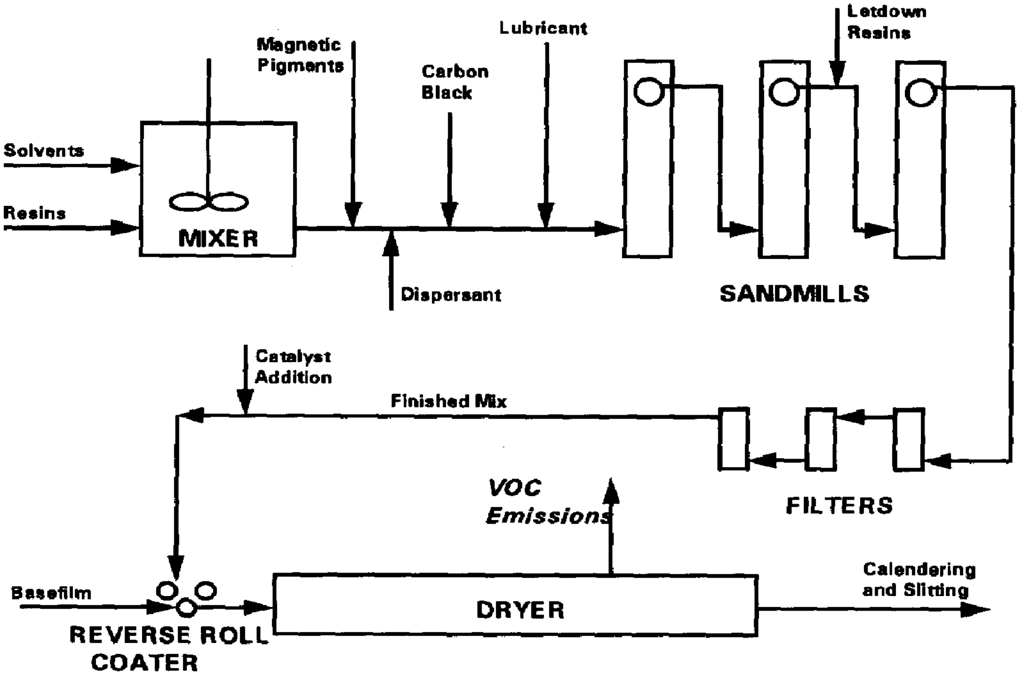

Fig. 4. Magnetic tape manufacturing process.

emission of 0.84 kmol/s. This gaseous emission contains VOCs in the form of tetrahydrofuran (THF), methyl ethyl ketone (MEK), toluene, and cyclohexanone. The mole fractions of these compounds in the gaseous emission are 7.23×10^{-4}, 8.65×10^{-4}, 1.14×10^{-4} and 8.49×10^{-4}, respectively. It is desired to design a network of refrigeration units that can recover 95% of these VOC vapors via condensation. This separation task corresponds to cooling the gaseous stream to a temperature of 193 K (as computed through Eqs. (4)–(6)). As has been mentioned earlier, the cold gas exiting the refrigeration processes is used to pre-cool the gas entering the refrigeration network down to 274 K. This pre-cooling allows the dehumidification of the emission stream prior to further cooling of this stream in the refrigeration network to condense the desired quantity of VOCs. The remaining cooling duty from 274 to 193 K is to be carried out using refrigerants.

Several types of refrigerants are available for VOC condensation. Typically, organic refrigerants referred to as CFCs (chlorofluorocarbons) are used for industrial refrigeration processes. However, manufacturers of CFCs must cease production by the end of 1995 because of the potential of these compounds to deplete the ozone layer. Substitute refrigerants in the form of HCFCs (hydrochlorofluorocarbons) and HFCs (hydrofluorocarbons) are now being produced since they pose little to no ozone depletion potential [9, 10]. Three commercially available substitute refrigerants; HCFC 142b (1-chloro-1,1-difluoroethane), HFC 134a (1,1,2,2-tetrafluoroethane), and HCFC 22 (chlorodifluoromethane), will be considered in this case study, along with two substitute refrigerants which are currently under development; HFC 143a (1,1,1-trifluoroethane) and HFC 125 (pentafluoroethane). In addition to these substitute CFC refrigerants, three inorganic refrigerants, liquid ammonia, liquid sulfur dioxide, and liquid nitrogen will be considered for this case study.

The first step in solving the case study involves the generation of the STD. The STD for the multicomponent VOC recovery problem is constructed as shown by Fig. 5. The cost per kJ of refrigeration associated with each refrigerant is shown in the representative unit boxes. These costs are evaluated through the equations in Appendix A. Analysis of the STD indicates that refrigerants HCFC 142b, HFC 143a, HCFC 22 can be removed from branch one due to their higher cost per kJ than liquid N_2 refrigerant. Additionally, HCFC 142b can be removed from branch one due to their higher cost per kJ than liquid SO_2 refrigerant. This procedure is continued for each branch of the STD and allows the development of the completed MUSTD as shown by Fig. 6. The values of CM_n were then calculated for each branch of the MUSTD. Using the minimum utility formulation, P1, the optimum distribution of gaseous flow rates g_1–g_9 was found to be 0.44, 0, 0, 0, 0.40, 0, 0, 0, 0 kmol/s respectively. The results of the optimization program were obtained using the software LINDO [11] in 2 CPU seconds using a Gateway 486, 66 MHz, computer. As mentioned previously, the gaseous flow rates from branches g_1 and g_5 can be combined into a single refrigeration unit based on the sixth-tenth factor rule. Hence, one can construct a network featuring minimum number of units which satisfies the minimum energy cost obtained by solving P1. This MUSTD refrigeration network is shown in Fig. 7. The numbers inside the boxes correspond to the total annualized cost of each unit. Fixed costs for the refrigeration units are given in Appendix A. A 10-year life is assumed for each

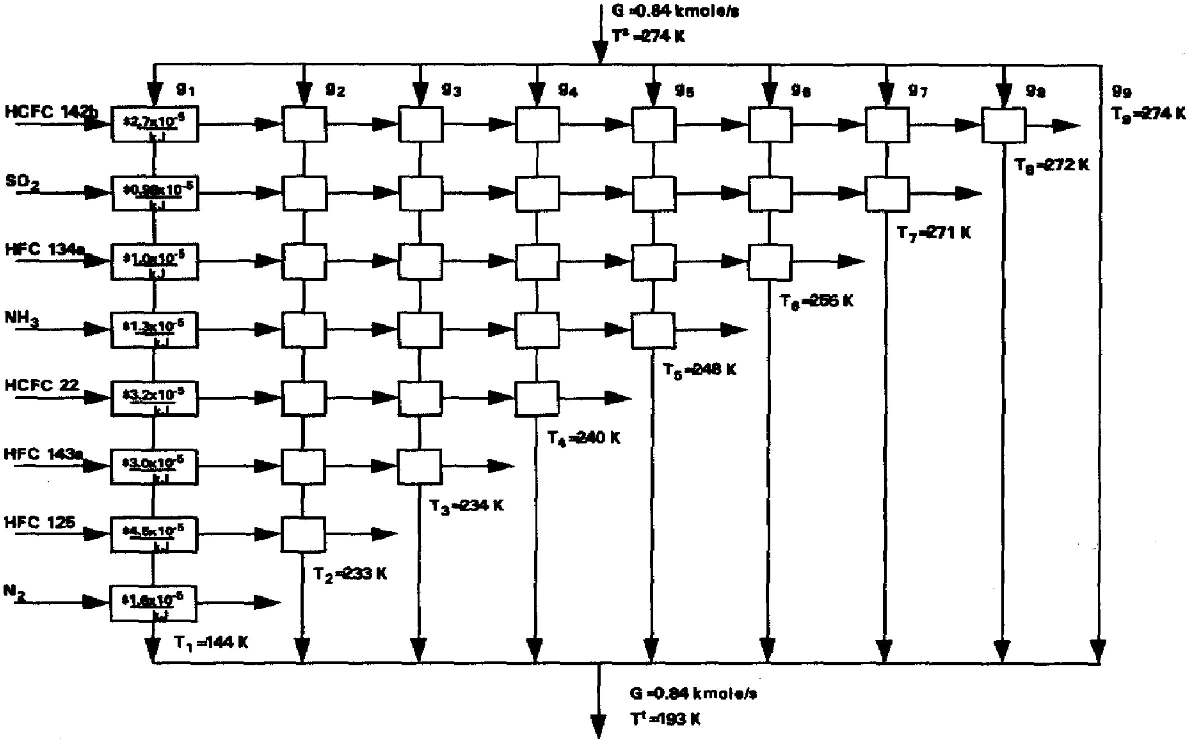

Fig. 5. STD for the VOC emission case study.

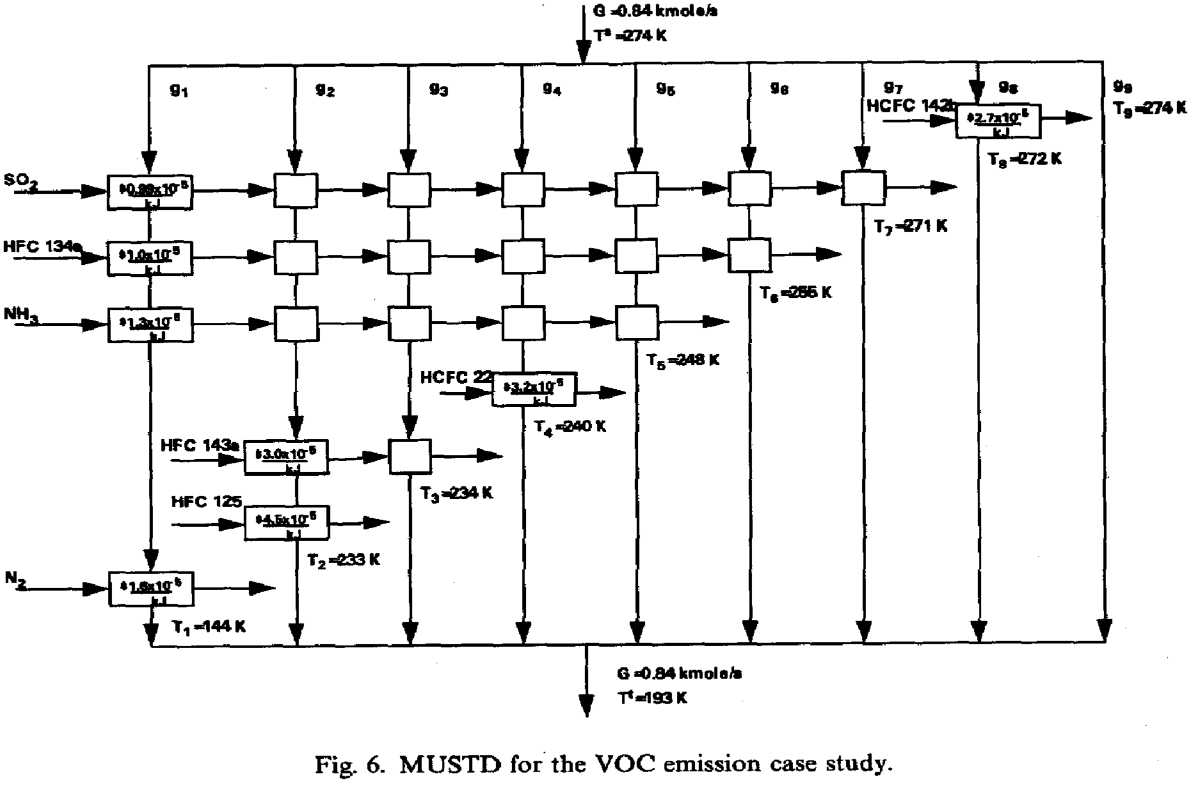

Fig. 6. MUSTD for the VOC emission case study.

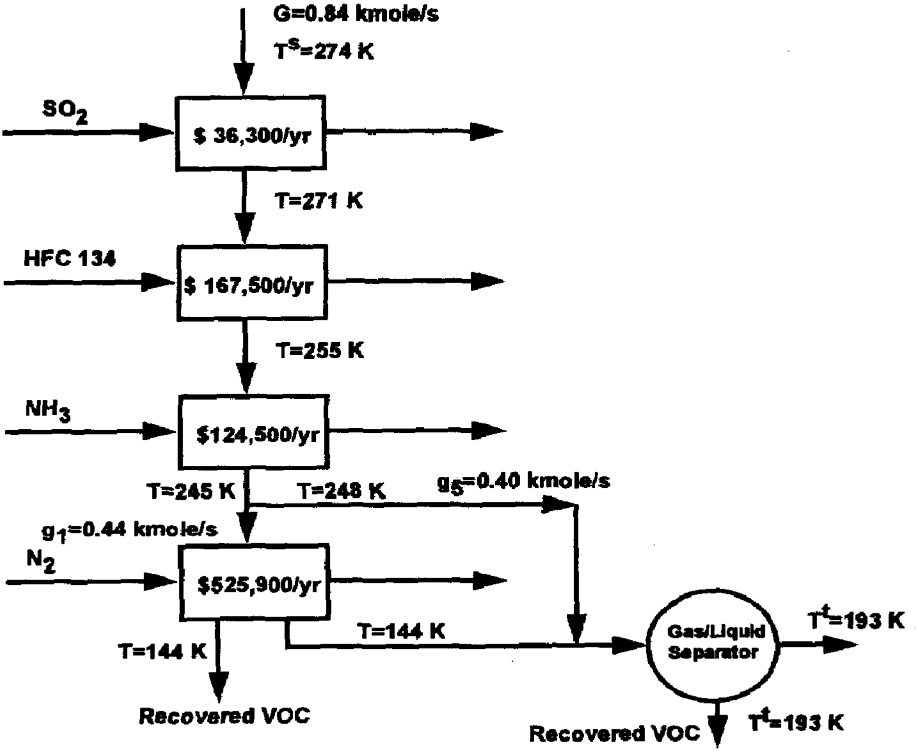

Fig. 7. A VOC condensation network featuring minimum number of units satisfying the minimum energy cost (numbers inside boxes correspond to total annualized costs).

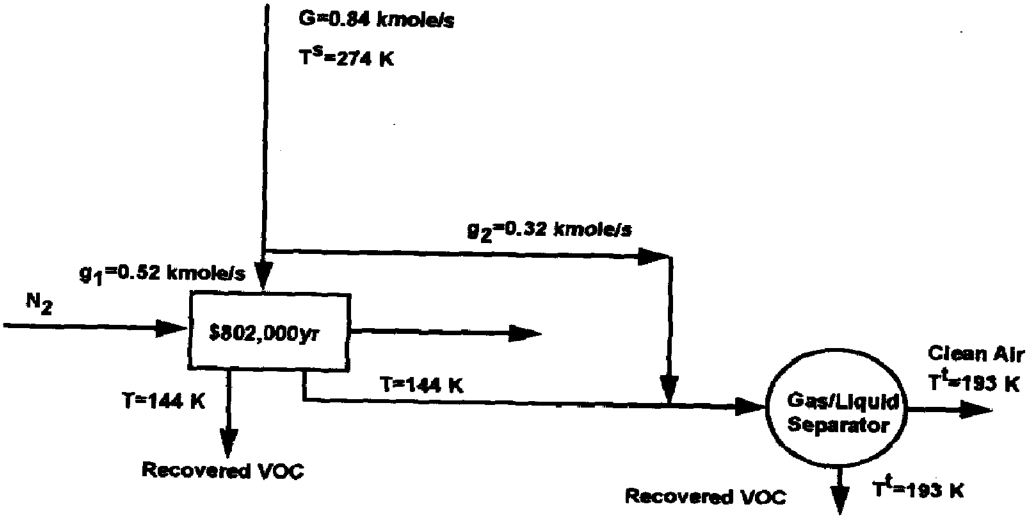

Fig. 8. Optimal system (MACNET) for the VOC recovery problem with no heat integration (numbers inside boxes correspond to total annualized costs).

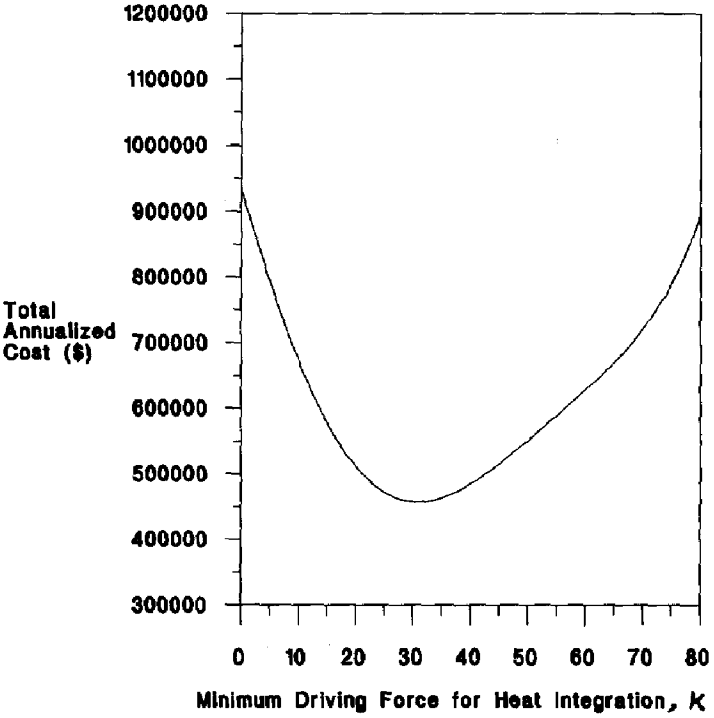

Fig. 9. Optimal heat integration for the VOC recovery problem.

refrigeration system. By conducting the operating/fixed costs tradeoff procedure previously described, the MACNET shown in Fig. 8 is generated. These tradeoffs result in the elimination of SO_2, HFC 134 and NH_3 from the network. Hence, the minimum annualized cost network, MACNET, involves refrigeration using N_2 only. The total annualized cost of this system is $802 000/yr. This MACNET was determined with no heat integration between the "hot" gaseous emission stream and the "cold" portion of this stream after the VOC is condensed. Several MACNETs were then determined at various levels of heat integration and the resulting affect of the tradeoff between refrigeration cost and heat transfer surface area are indicated in Fig. 9. The final MACNET incorporating the optimal amount of heat integration is shown in Fig. 10. Having designed an optimal VOC condensation system, we are now in a position to separate the VOCs using distillation.

10. Distillation network optimization for the VOC recovery problem

A distillation network allowing the separation of the four VOCs recovered is designed based on the configuration shown in Fig. 11. A two stage procedure is used to optimize this distillation network based on a minimum separation purity of 99 mol% for each of the VOCs. ASPEN Plus simulation software is employed for the distillation optimization [12]. The first stage involves the identification of the

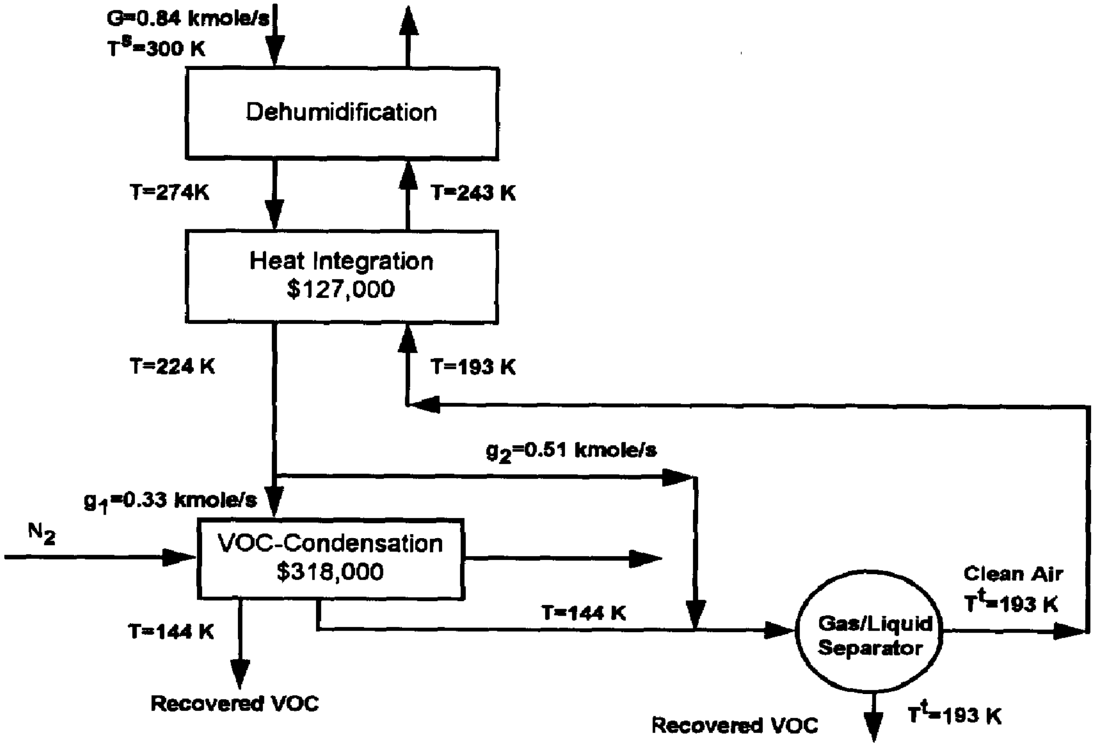

Fig. 10. MACNET for the VOC recovery problem with optimal heat integration (numbers inside boxes correspond to total annualized costs).

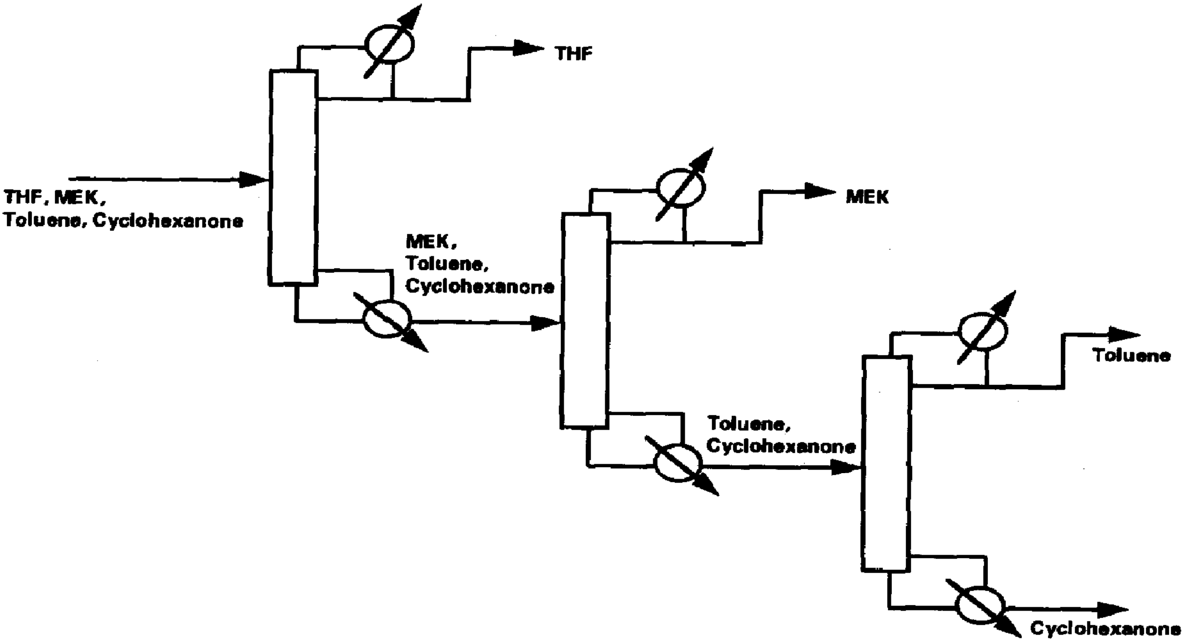

Fig. 11. Distillation network for VOC separation.

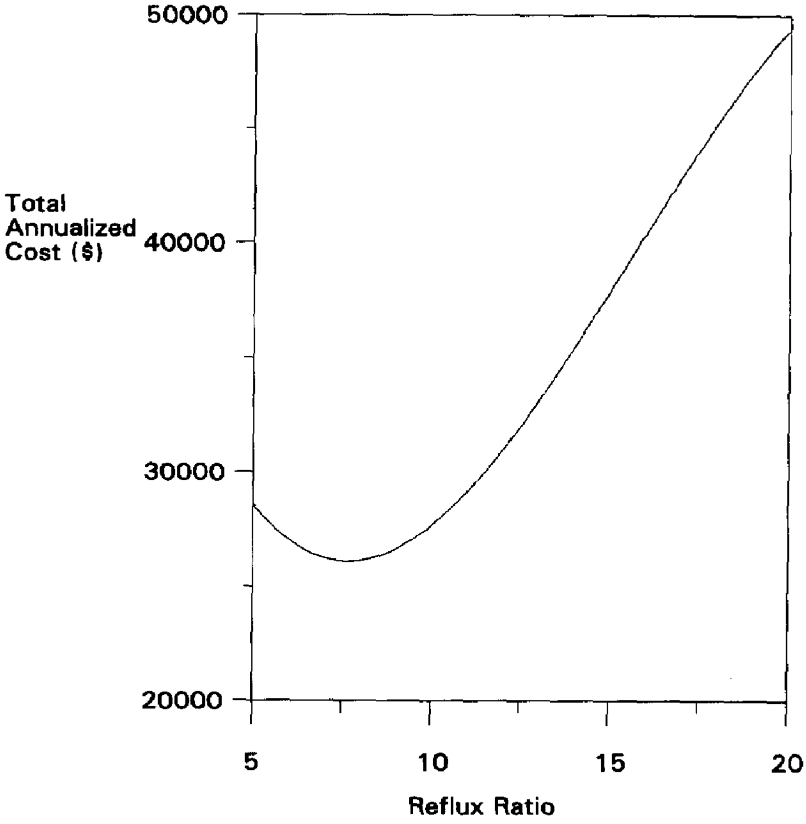

Fig. 12. Optimal reflux ratio for toluene–cyclohexanone distillation column.

optimum feed tray for each column. This can be determined by varying the feed location at a constant reflux ratio and column size. The feed location resulting in the highest purity of the desired VOC as the top product is identified as the optimum feed tray location.

Stage two of the optimization allows for tradeoff considerations between the fixed and operating costs of each column. Columns containing varying numbers of trays are modelled. The optimum feed tray location is used for each column size and the minimum reflux ratio needed to satisfy the 99 mol% purity is determined. The fixed and operating costs for each column size at the minimum reflux ratio are then determined. For instance, Fig. 12 indicates results for the toluene/cyclohexanone separation column and illustrates that there is a reflux ratio that corresponds to the minimum total annualized cost for the column. This optimization procedure resulted in a distillation network with a total annualized cost of $127 000/yr.

It is worth pointing out that the value of the VOC recovered is $7 150 000/yr while the total cost of the optimal MACNET/distillation is $572 000/yr. This results in a net annual revenue of $6 578 000/yr. It is interesting to compare the optimum design with alternative refrigeration networks. A summary of alternative VOC-condensation systems linked with the optimal distillation configuration is presented in Table 1. As expected, the MACNET with optimal heat integration/distillation configuration

Table 1
Comparison of alternative, non-optimal VOC condensation/distillation networks

Network summary	Total annualized cost
Optimal MACNET with 50 K heat integration: N_2 followed by distillation	\$572 000
MACNET with no heat integration: N_2 followed by distillation	\$929 000
NH_3 and N_2 with no heat integration followed by distillation	\$1 142 000
HFC 125 and N_2 with no heat integration followed by distillation	\$1 945 000
SO_2 and NH_3 with no heat integration followed by distillation	Cannot achieve desired environmental objective

developed by the proposed procedure offers the minimum cost for undertaking the VOC-recovery task.

11. Conclusion

We have developed a novel procedure for designing VOC condensation systems for multicomponent gaseous VOC emissions. This procedure involves a three-stage targeting approach. In the first stage, minimum energy cost is identified via the notions of STD and MUSTD. In the second stage, a network is synthesized to feature the minimum number of coolers/condensers while realizing the minimum operating cost of the system. In the third stage, tradeoffs between the operating and fixed costs are evaluated to yield the minimum annualized cost of the network. The condensed VOCs are then fed to a distillation sequence that separates them into individual streams. A case study on recovering multiple VOCs from gaseous emissions of a magnetic tape manufacturing plant was solved to demonstrate the applicability of the proposed procedure.

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Nomenclature

CH_n	cost of the *n*th refrigerant expressed as \$/kJ removed
CM_n	cost of cooling/condensing the *n*th portion of the STD, expressed as \$/kg mol of waste stream cooled

C_{P_n}	average specific heat of the gaseous waste passing through the *n*th portion of the STD, kJ/kmol K
C_p^L	specific heat of the liquid refrigerant, kJ/kmol K
F_{ref}	flow rate of refrigerant, kg/s
g_n	the flow rate of the *n*th portion of the waste stream on the STD, kmol/s
G	flow rate of the gaseous waste, kmol/s
h^s	enthalpy of the gaseous waste at T^s, kJ/kg
h_n	enthalpy of the gaseous waste at T_n, kJ/kg
ΔH^v	latent heat of vaporization of refrigerants, kJ/kg
n	index for portions of gaseous waste on the STD or index for refrigerants
NE	number of available refrigerants
N_V	number of VOCs
$P_i^0(T_n)$	vapor pressure of the *i*th VOC at temperature T_n, Pa
$P_i^0(T_i^c)$	vapor pressure of the *i*th VOC at temperature T_i^c, Pa
P	total pressure of the gaseous waste, Pa
$Q_{condenser}$	heat removed from the refrigerant in the condenser, KJ/s
$Q_{evaporator}$	heat removed by the refrigerant in the evaporator, KJ/s
T_{cond}	temperature of the refrigerant leaving the condenser, K
T_{evap}	temperature of the refrigerant leaving the evaporator, K
T_n	temperature of the gaseous stream leaving *n*th portion of the STD, K
T^c	temperature at which condensation of the VOC begins, K
T_i^c	temperature at which condensation of the *i*th VOC begins, K
T^s	supply temperature of the gaseous waste, K
T^t	temperature of the gaseous waste leaving the VOC-recovery network, K
$W_{compressor}$	work performed by the compressor, kJ/s
y_n	mole fraction of the VOC in the gaseous stream leaving the *n*th portion of the STD
y^s	supply composition of the VOC in the gaseous waste
y^t	target composition of the VOC in the gaseous waste
y_i^s	supply composition of the *i*th VOC in the gaseous waste
y_i^t	target composition of the *i*th VOC in the gaseous waste
$y_{n,i}$	composition of the *i*th VOC exiting the *n*th branch of the STD, MUSTD

Greek letters

λ	latent heat of vaporization of VOC, kJ/kg
η	fractional recovery of VOCs
η_i	fractional recovery of the *i*th VOC

Appendix A: Basis of economic calculations

A.1. Operating cost equations

Total operating cost for the n^{th} refrigerant

"CH_n" = operating cost of compressor + operating cost of condenser

$$= \frac{1}{Q_{\mathrm{evaporator},n}}\left[\frac{W_{\mathrm{compressor},n}\ (\mathrm{kW})\cdot \text{electric energy cost } (\$/\mathrm{kWh})}{\eta_{\mathrm{compressor}}} + \frac{Q_{\mathrm{condenser},n}\cdot \text{cost of cooling water } (\$/\mathrm{kg})}{(C_p \Delta T)_{\mathrm{cooling\ water}}}\right], \tag{A.1}$$

where $W_{\mathrm{compressor},n}$, $Q_{\mathrm{condenser},n}$ and $Q_{\mathrm{evaporator},n}$ can be evaluated through the following expressions [13,14]:

$$W_{\mathrm{compressor},n} = \left[\left(\frac{T_n^{\mathrm{cond}} - T_n^{\mathrm{evap}}}{T_n^{\mathrm{evap}}}\right)\Delta H_n^v\right] F_{\mathrm{ref}}, \tag{A.2}$$

$$Q_{\mathrm{condenser},n} = \left[\Delta H_n^v \frac{T_n^{\mathrm{cond}}}{T_n^{\mathrm{evap}}} - C_{pn}^{\mathrm{L}}(T_n^{\mathrm{cond}} - T_n^{\mathrm{evap}})\right] F_{\mathrm{ref}}, \tag{A.3}$$

$$Q_{\mathrm{evaporator},n} = \left[\Delta H_n^v - C_{pn}^{\mathrm{L}}(T_n^{\mathrm{cond}} - T_n^{\mathrm{evap}})\right] F_{\mathrm{ref}}. \tag{A.4}$$

The following data were used in the VOC case study: Cost of cooling water, $\$6.06 \times 10^{-4}$/kg; Cost of electric energy, $\$8.25 \times 10^{-2}$/kWh.

The latent heats of vaporization for HCFC 142b, SO_2, HFC 134, NH_3, HCFC 22, HFC 143a, HFC 125, and N_2 are 213, 381, 208, 1361, 232, 229, 157 and 198 kJ/kg, respectively, at an evaporator operating pressure of 5 psig [16–21].

A.2. Fixed cost equations

Refrigeration

The fixed costs (\$) for the refrigeration systems were based on the following equations [15]:

$$\text{Fixed cost of } SO_2 \text{ system} = 7877\ (\text{Tons refrigeration}) + 9959, \tag{A.5}$$

$$\text{Fixed cost of HFC 134 system} = 6145\ (\text{Tons refrigeration}) + 26\,722, \tag{A.6}$$

$$\text{Fixed cost of } NH_3 \text{ system} = 10\,652\ (\text{Tons refrigeration}) + 13\,485. \tag{A.7}$$

Since nitrogen is typically a once-through system, the fixed cost of the system is primarily that of a tank holding liquified nitrogen. The fixed cost of this tank was estimated to be \$120 000.

The fixed costs (\$) for the condensers were based on data available in the US EPA, (1991) document and on data available in Peters and Timmerhaus [8].

The annualized fixed cost is obtained for the above systems by dividing the fixed cost of each unit by a useful life period of 10 years.

Distillation

Bubble cap distillation columns were used for the ASPEN simulation. Capital costs of distillation column shells, trays, reboilers and condensers were determined from data available in Peters and Timmerhaus [8].

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