FURTHER DEVELOPMENT OF A MIXED GAS JOULE THOMSON REFRIGERATOR

A. Alexeev, Ch. Haberstroh, H. Quack

Technische Universitaet Dresden,
Lehrstuhl für Kaelte- und Kryotechnik

ABSTRACT

A mixed gas Joule Thomson refrigerator has distinct advantages over other cryocooler for certain applications. The system is compact, has good thermodynamic efficiency and low levels of vibration and noise. Further development of this refrigeration machine is possible by optimization of the gas mixture composition. A method was developed which permits a reduction by a large factor in the number of simulation calculations and thus shortens the optimization time considerably.

INTRODUCTION

General requirements for a cooler are reliability (long maintenance-free time) and low cost. Further criteria are connected with applications for high temperature superconductors (HTS). Good temperature stability and low levels of mechanical vibration and electromagnetic interference are necessary.

Measurements have been published[1,2] that show that temperature fluctuations as well as mechanical disturbances caused by a mixed gas Joule Thomson refrigerator are considerably lower compared with regenerative refrigeration machines (Gifford-McMahon and Stirling refrigerator) which work with pulsation of the gas. For these reasons the recuperative mixed gas cycles have a better chance for use in SQUID cooling than regenerative coolers.
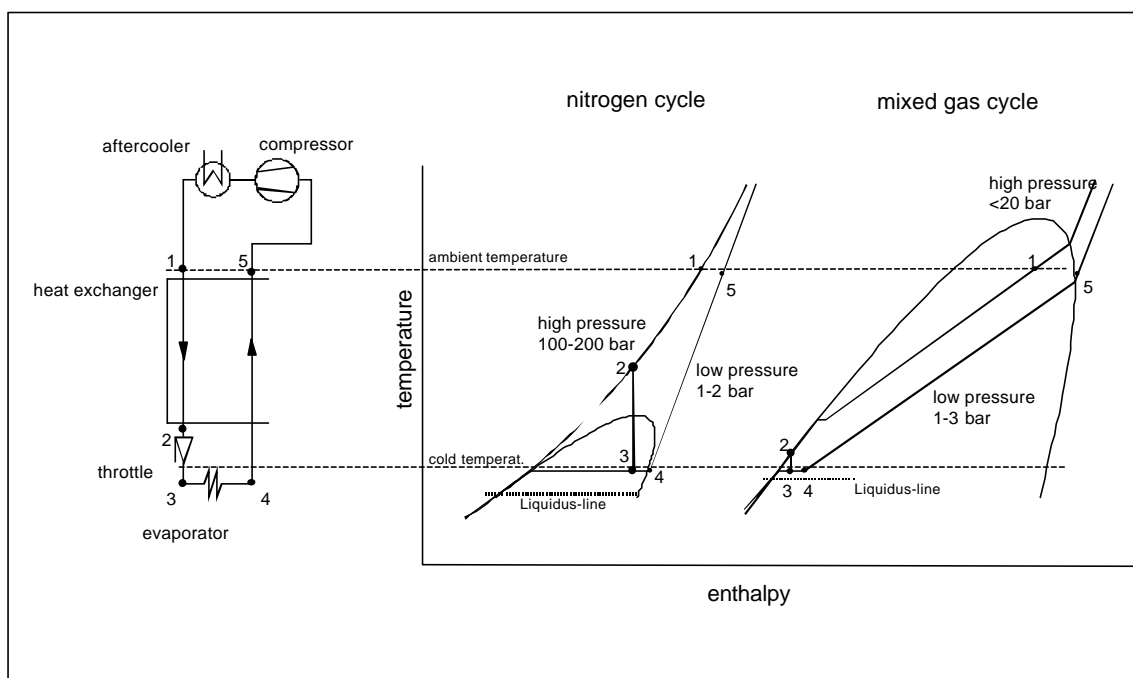
MIXED GAS JOULE THOMSON CYCLE

In a Joule Thomson system throttling expansion of the gas is combined with recuperative precooling. The main cycle components are the compressor, heat exchanger, throttle valve and evaporator.

In the "classic" Joule Thomson cycle with a pure refrigerant the gas is discharged from a compressor and passes through the counterflow heat exchanger, where it is cooled by the returning low pressure gas. In the throttle valve the high pressure gas expands into the vapor-liquid area; the liquid evaporates in the evaporator with absorption of energy, the vapor is warmed in the heat exchanger and compressed again (Fig. 1).

In contrast to the Joule Thomson process with a pure refrigerant the mixed gas cycle almost completely works in the vapor-liquid region. The first liquid in the high pressure stream appears almost at ambient temperature. The high pressure stream is cooled down in the heat exchanger and further condensed at a sliding temperature, so that the refrigerant is completely in the liquid phase before entering the throttle valve. In the evaporator the refrigerant only partially evaporates. The low pressure stream continues to boil in the heat exchanger at continually rising temperature (Fig. 1).

These gas mixtures consist of a combination of gases with normal boiling temperature below 320 K. Nitrogen, hydrocarbons and their halogen derivatives, inert gases and other chemical substances can be used.

The gas is typically discharged at $p_{high} = 15\text{-}20$ bar with a suction pressure $p_{low} = 1\text{-}3$ bar. A low cost oil lubricated hermetic compressor can be used. The maintenance-free time of these machines exceeds by far 20,000 hours. Thereby the high reliability of the cooler is guaranteed, because no other mechanically moving components are necessary. The use of an oil lubricated compressor however has the disadvantage of oil contamination in the high pressure stream. This would result in clogging in the cold box. Therefore an oil separation in the high pressure gas after the compressor is required.

Fig. 1 Joule Thomson cycles

A prototype of a mixed refrigerant Joule Thomson cooler with 2 W cooling power at 77 K was developed and built at the Technische Universitaet Dresden.

The cold box consists of a cryostat 160 mm in diameter and approximately 300 mm in length (Fig. 2). In the upper flange connections for pressure lines and electric feedthroughs are placed. A multi- tube heat exchanger was used.

The oil lubricated compressor of a conventional air conditioning system was used. The electric power consumption of this machine is about 0.4 kW. The pressure lines are made of nylon. This way compressor and cold box are electrically separated. The mechanical vibrations are considerably reduced too.

POSSIBLE FURTHER DEVELOPMENTS

The desired parameters could be reached already with the described cooler[3]. From the investigations it could be seen that this JT cooler has considerable potential for optimization.

Fig. 2 A prototype of a mixed gas Joule Thomson cooler developed at the TU Dresden

Certain technical losses can be reduced by further development of the compressor unit and heat exchanger. Considerable improvements can be reached by adjustment of working parameters such as the high and low pressure. The largest optimization potential, however, is connected with optimization of the gas mixture composition as it was shown by previous calculations[4].

The aim of the optimization is to optimum the mixture composition and determine the optimum high and low pressures for the required cooling temperature and other given parameters. It is a set of parameters, at which the efficiency of the whole system is maximal. Mathematically it can be defined as follows:

$$CF = \frac{Q_0}{P} \cdot \frac{T_{amb} - T_0}{T_0} = CF\ (T_{amb}, \Delta T_{min}, T_0, p_h, p_n, z_i) \Rightarrow MAXIMUM\ ,\ \text{whereby}$$

CF - Carnot Fraction
Q_0 - cooling power
P - electric power consumption of the compressor
T_{amb} - ambient temperature
T_0 - cold temperature
$\boldsymbol{D}T_{min}$ - minimal temperature difference in the heat exchanger
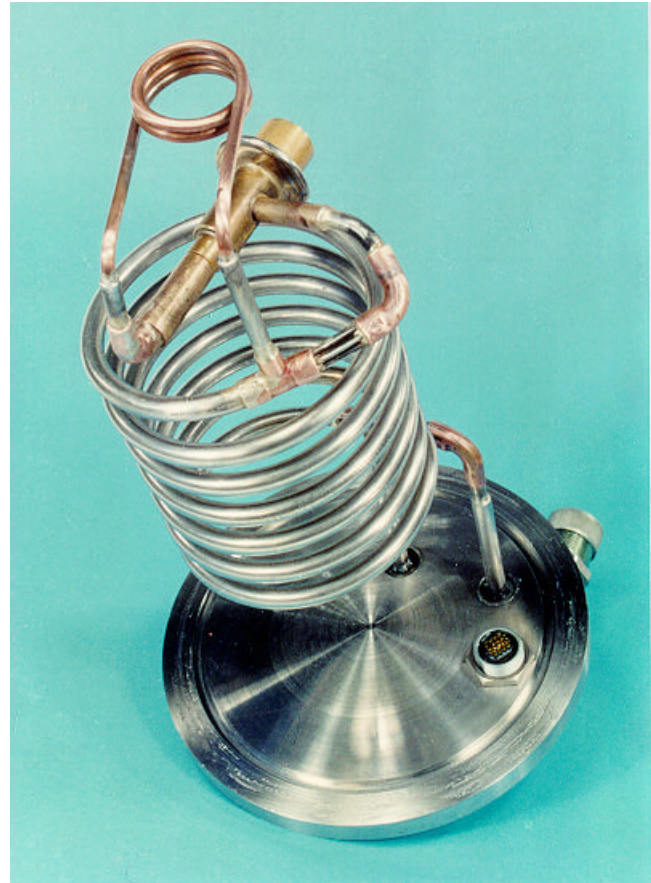p_h, p_l - high and low pressures
z_i - mixed gas composition (molar %), this parameter contains 4 free parameters
        if a five component mixture is used.

For simplification we assumed as follows:

- the mixture does not form a solid phase
- the mixture composition does not change in the cycle
- no heat load from the insulation or by heat conduction
- no pressure losses in the heat exchanger

Thermodynamic Considerations

To understand the thermodynamic behavior better we have made a series of calculations. For a set of input parameters the specific refrigeration power of the cycle was calculated. The concentrations of components were varied and changes in efficiency were determined. From these results a systematic understanding was developed.

The calculations were accomplished for a mixture of nitrogen, methane, ethane, propane and butane. The software package PROVISION[5] was used.

Results of the Simulation. By systematic variation of the mixture composition and numerical calculation of the cycle the following relationships were found:

a) the mixture composition has a dominant influence on the efficiency

b) in a 3D diagram, with the concentrations of the high volatile components on the horizontal axes and the cooling power as the vertical axis, a three-sided asymmetrical pyramid is obtained (Fig. 3); the lateral surfaces differ in their gradients; the two low volatile components are kept constant

a) by variation of the concentration of the low volatile components a similar result as in b) is obtained only with other maxima

b) the optimal relation between nitrogen and methane concentrations for the assumed conditions ($p_h = 18$ bar, $p_l = 1$ bar, $T_0 = 80$ K) can be described by the equation $z_{CH4} = 1.3659 \, z_{N2} - 17.962$ mol % for all compositions of low volatile components

c) in a 3D diagram with the concentrations of the low volatile components on the horizontal axes and the cooling power as vertical axis a surface in the form of a three-sided asymmetrical pyramid with a maximum by $z_{C3H8} \gg 10$, $z_{C4H10} \gg 20$ mol % is obtained (Fig. 4); one side of this figure has a break along a straight line.

The change of the CF can be described essentially as a linear function of certain mixture components; there are no indications of additional local maxima, which could be caused by the complicated thermodynamic behavior.

This allows one, with some caution, to
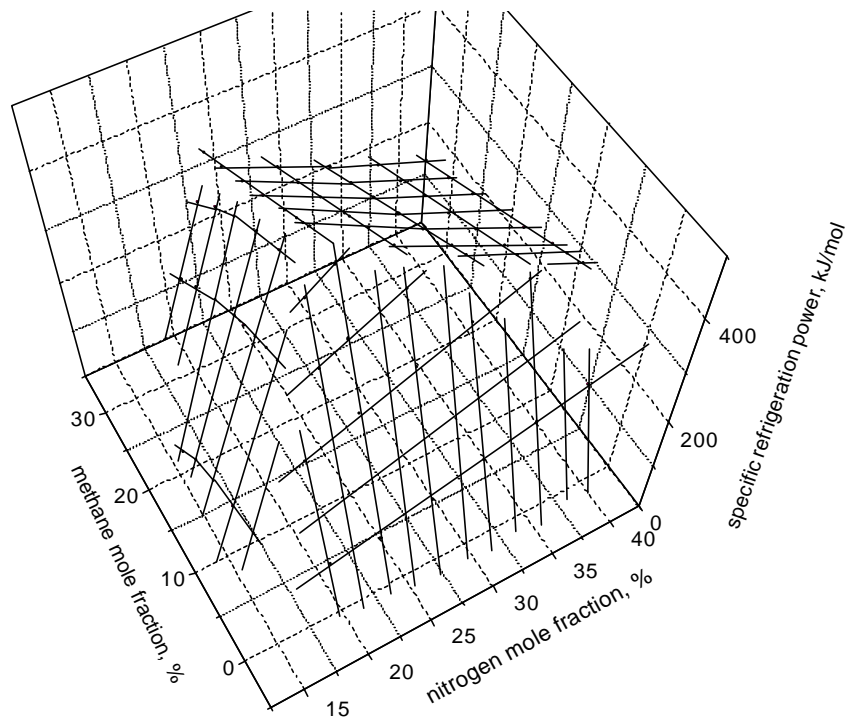
Fig. 3 specific refrigeration power of the mixed gas JT cycle, $T_0 = 80$ K, $p_h = 18$ bar, $p_l = 1$ bar, $z_{propane} = 15$ mol %, $z_{butane} = 1$ mol %

draw the conclusion, that it is possible to describe the efficiency of the cycle relatively simply, and to find an optimal mixture configuration for a given requirement very fast.

Analysis of the Results. To understand the observations described above the typical temperature-duty (*T-q*) diagram for the heat exchanger should be considered (Fig. 5).

Three relevant points (at $T \gg 80\,K$, $T \gg 270\,K$ and $T \gg 120\,K$) can be distinguished here. The reason for the existence of these points can be found in the thermodynamic behavior of the phases.

The first break in the *T-Q* diagram corresponds to the first liquid phase. At the example considered here the condensation of low volatile components begins at about $T \gg 270\,K$. The second critical break is connected with the liquefaction of the second liquid phase and is very important for the description of the mixed gas JT cycle.

The specific cooling power of the JT process is given by the enthalpy difference between the high and low pressure streams in each point of the heat exchanger with the condition that no pinch point in the heat exchanger exists:

$$q_0 = \Delta h_{n-h}$$

A pinch point can appear at one of the three critical points in the recuperator: at the warm end, at the cold end and at the point, where the second liquid phase starts to condense in the high pressure stream (split point):

$$\Delta T_{min} = min \begin{Bmatrix} \Delta T_{min}^{warm\,end} \\ \Delta T_{min}^{split\,point} \\ \Delta T_{min}^{cold\,end} \end{Bmatrix}$$

This relationship can be applied to understand the lateral surfaces of the pyramid visible in Fig. 3.

First surface

The mixture compositions correspond to a pinch point at the warm end of the heat exchanger creating a softly bent surface (in Fig. 3 in the back). The gradient corresponds to the concentration of the low volatile components in the mixture.

surface 1:

$$max\{q_0\} = q_0^{(1)} = \Delta h_{l-h}^{we}$$
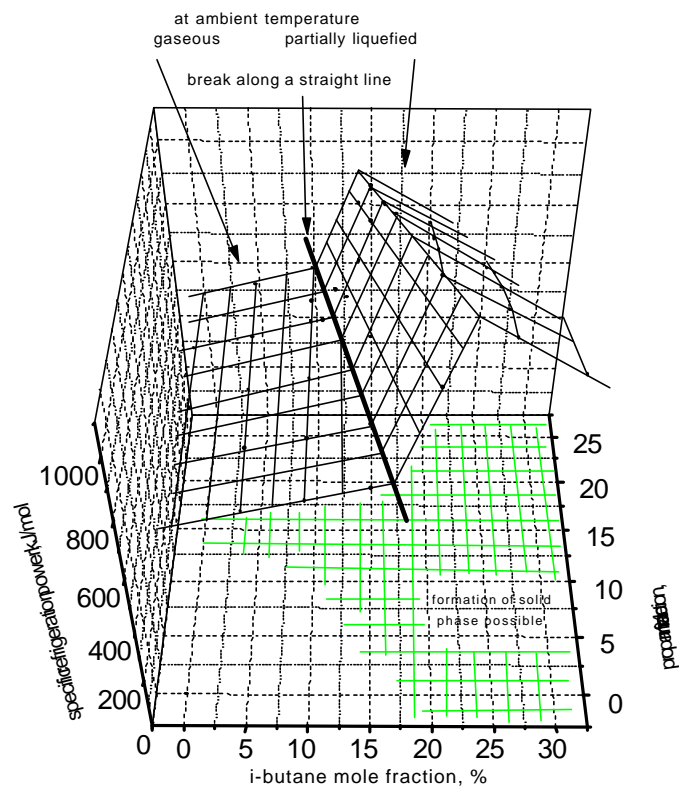
Fig. 4 specific refrigeration power of the mixed gas JT cycle, $T_0 = 80\,K$, $p_h = 18$ bar, $p_l = 1$ bar
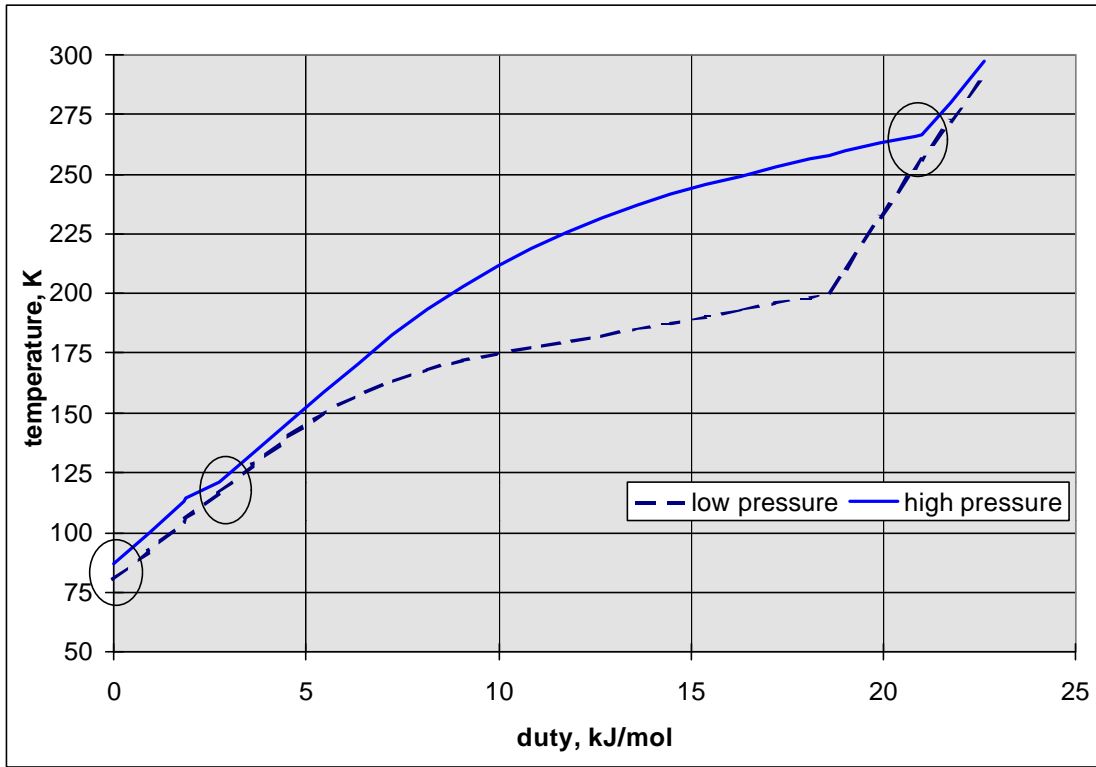
Fig. 5 typical temperature duty diagram for heat exchanger,
nitrogen-hydrocarbons mixture, $T_{amb}=297$ K, $T_0 = 80$ K, $\Delta T_{min}= 5$ K

This can be described as:

$$q_0^{(1)} = h\left(p_l, T_{amb} - \Delta T_{min}\right) - h\left(p_h, T_{amb}\right) \tag{1}$$

The specific cooling power can be described here as a linear function of the concentration of the low volatile components:

$$q_0^{(1)} \approx Const_1 + \sum_{i=3}^{n} z_i \cdot Coefficient_i \tag{2}$$

Second surface

The mixture compositions causing a pinch point at the cold end of the heat exchanger create the very steep surface (in Fig. 3 left side):

surface 2: $\qquad \max\{q_0\} = q_0^{(2)} = \Delta h_{l-h}^{cold\ end}$

The specific refrigeration power in this case depends almost completely on the concentration of the highest volatile component (nitrogen).

$$q_0^{(2)} \approx z_1 \cdot Coefficient_1 + Const_2 \tag{3}$$

Third surface

Other mixture compositions corresponding to a pinch point in the middle of the heat exchanger present the steep surface (in Fig. 3 in front):

surface 3: $\qquad \max\{q_0\} = q_o^{(3)} = \Delta h_{l-h}^{split\ point}$

The specific refrigeration power in this case depends on the concentration of the second highest volatile component (methane):

For that reason surfaces 2 and 3 correspond to the concentrations of the nitrogen (z_1) and methane (z_2) respectively. The intersection of these surfaces is a straight line $z_{CH4} = A\, z_{N2} - B$.

$$q_0^{(3)} \approx z_2 \cdot Coeffcient_2 + Const_3 \qquad (4)$$

Break Line

The break line of the plane in front in Fig. 4 corresponds to the phase change in the high pressure stream at ambient temperature. Mixtures above this line have an increased concentration of low volatile components. The refrigerant is partially liquefied at the warm end of the heat exchanger in this case. These mixtures are preferable from the thermodynamic point of view. The specific refrigeration power achievable in this case is approximately two times better compared with the gaseous mixtures at ambient temperature.

Optimization Strategy

An optimization strategy was developed based on the knowledge described above. The global maximum is determined in a two-dimensional field only of the concentrations of low volatile components $z_5 = z_5^{(begin)} ... z_5^{(end)}$ and $z_4 = z_4^{(begin)} ... z_4^{(end)}$. The optimization procedure is considerably simplified that way and can be done in a short time.

This is done by regarding only the optimal concentrations of the high volatile components (instead of all possible) for each alleged pair (z_4, z_5). The search of these optimal concentrations of the high volatile components is realized by an effective and very fast algorithm. This is presented in Fig. 6 schematically.

The optimization begins with the calculation of the enthalpy differences at critical points of the heat exchanger for three alleged concentrations of the high volatile components. The calculated data interpolated are by plan equation. The optimum is defined as intersection of the three surfaces.

Because the surfaces are assumed as even surfaces, an error in the result is possible. The result should therefore be corrected with the same algorithm.

This method allows a fast maximum search in the whole area of the components concentrations.

OUTLOOK

The mixed gas Joule Thomson refrigerator offers distinct advantages for the cooling of supersensitive components. The machine is simple in construction and is compact. The maintenance-free time amounts to far more than 20,000 operating hours. Magnetic and mechanical disturbances at the cold finger are less than for regenerative cooling system.

A further development of this cooler is possible by optimization of the gas mixtures. A strategy was developed which allows one to shorten the calculation time and to accelerate the optimization considerably.

The accomplished calculations show, that mixtures with increased concentrations of low volatile components like propane or butane are thermodynamically preferable. The refrigerant is partially liquefied at the warm end of the heat exchanger in this case. Howewer, use of these mixtures is connected with two problems:

- formation of solid phase at low temperatures, and clogging in cold box is possible
- local mixture composition can be changed by transport of the two-phase fluid from the compressor to the cold box

But these problems can be overcome in principle. The hardware must be adjusted accordingly. Future work should focus on this point.

$$
\begin{array}{|c|}
\hline
\text{1: DATA INPUT:} \\[4pt]
z_1^{(1)}; \qquad z_1^{(2)} = z_1^{(1)} + \Delta z_1; \qquad z_1^{(3)} = z_1^{(1)}; \\[4pt]
z_2^{(1)}; \qquad z_2^{(2)} = z_2^{(1)}; \qquad z_2^{(3)} = z_2^{(1)} + \Delta z_2; \\[4pt]
z_3^{(i)} = 1 - z_1^{(i)} - z_2^{(i)} \qquad i = 1..\,3 \\
\hline
\end{array}
$$

$$
\begin{array}{|c|}
\hline
\text{2: CALCULATION OF ENTHALPY DIFFERENCES} \\
\text{AT CRITICAL POINTS OF HE:} \\[4pt]
\Delta h_1^{(i)} = \left| h_{T_{amb}}^{p_h} - h_{T_{amb}-\Delta T_{\min}}^{p_l} \right| \\[6pt]
\Delta h_2^{(i)} = \left| h_{T_{split}^{p_h}}^{p_h} - h_{T_{split}^{p_h}-\Delta T_{\min}}^{p_l} \right| \qquad i = 1..\,3 \\[6pt]
\Delta h_3^{(i)} = \left| h_{T_0+\Delta T_{\min}}^{p_h} - h_{T_0}^{p_l} \right| \\
\hline
\end{array}
$$

$$
\begin{array}{|c|}
\hline
\text{3: INTERPOLATION OF CALCULATED DATA} \\
\text{BY PLAN EQUATION:} \\[4pt]
A_i \quad B_i \quad C_i \\[4pt]
A_i \cdot z_1^{(1)} + B_i \cdot z_2^{(1)} + C_i \cdot z_3^{(1)} = \Delta h_i^{(1)} \\[4pt]
A_i \cdot z_1^{(2)} + B_i \cdot z_2^{(2)} + C_i \cdot z_3^{(2)} = \Delta h_i^{(2)} \qquad i = 1..\,3 \\[4pt]
A_i \cdot z_1^{(3)} + B_i \cdot z_2^{(3)} + C_i \cdot z_3^{(3)} = \Delta h_i^{(3)} \\
\hline
\end{array}
$$

$$
\begin{array}{|c|}
\hline
\text{4: CALCULATION OF MAXIMUM AS INTERSECTION} \\
\text{OF THE THREE SURFACES:} \\[4pt]
z_1^{MAX} \qquad z_2^{MAX} \qquad z_3^{MAX} = 1 - z_1^{MAX} - z_2^{MAX} \\[4pt]
A_1 \cdot z_1^{MAX} + B_1 \cdot z_2^{MAX} + C_1 \cdot z_3^{MAX} = A_2 \cdot z_1^{MAX} + B_2 \cdot z_2^{MAX} + C_2 \cdot z_3^{MAX} \\[4pt]
A_2 \cdot z_1^{MAX} + B_2 \cdot z_2^{MAX} + C_2 \cdot z_3^{MAX} = A_3 \cdot z_1^{MAX} + B_3 \cdot z_2^{MAX} + C_3 \cdot z_3^{MAX} \\
\hline
\end{array}
$$

$$
\begin{array}{|c|}
\hline
\text{IF } \left| \left(\overline{z^{MAX}}\right)^{new} - \left(\overline{z^{MAX}}\right)^{old} \right| > \; \boldsymbol{e} \; \text{ DO: } \overline{z^{(1)}} = \overline{z^{MAX}} \quad \text{AND GOTO 1} \\[4pt]
\text{ELSE: END} \\
\hline
\end{array}
$$

Fig. 6 Algorithm to search of optimal concentration of high volatile components

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