Fractional distillation column design for hydrogen isotope separation

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Introduction

For the fusion energy field, gaseous hydrogen isotopes like deuterium and tritium are the postulated fuels. The pure form of each isotope can be separated, recovered and enriched using a cryogenic distillation process. For fusion applications, the deuterium-tritium streams are the desired products. In this paper, provisions will be made for the performances assessment of the already built Cryogenic Distillation (CD) system at ICSI when used for detritiation of different streams outside of the designed parameters. The evaluation is necessary due to the intent to connect the system to a Combined Electrolysis Catalytic Exchange (CECE) process for detritiation of low level tritiated heavy/light water. A block diagram of a facility for water detritiation based on CECE technology is illustrated in figure 1. Light tritiated water (HTO feed) is converted to gaseous hydrogen in the electrolyzer. This hydrogen is fed to the liquid phase catalytic exchange (LPCE) column, in which it participates in tritium isotopic exchange with tritium free water (H2O feed) fed to the top of the LPCE column. The HT stream that coming from a CECE processing low level tritiated light water is feed to a cryogenic distillation system. The purpose of the cryogenic system is to recover and enrich tritium from the tritiated stream of deuterium/hydrogen coming from the electrolyzer cell. Tritium will be stored on metal hydrides and a tritium depleted stream will be returned to the liquid phase catalytic exchange (LPCE) column which is a part of the CECE process. The assessment of the CD system is done using an in-house developed design and simulation software which is based on bubble-point method and tridiagonal matrix Wang-Henke method with an improved computational algorithm.

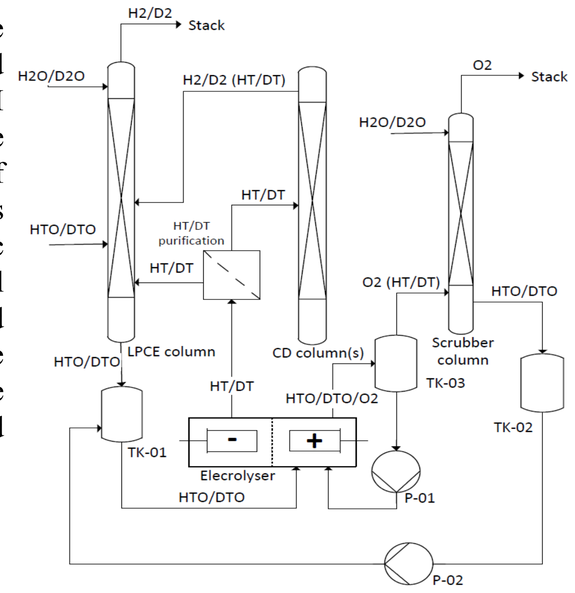

Fig. 1 CECE process connected to the CD system

Short description of the ICSI cryogenic distillation system

The CD system at ICSI Pilot Plant (figure 2) has been designed to detritiate a stream of tritiated deuterium coming from a LPCE column and consists of a four column cascade of different diameters ranging from 100 down to 8 mm, filled with structured and random packings and a maximum length of 6 m. Each column is equipped at the top with its own condenser connected to a 1000 W (at 20K) helium refrigeration unit which provides the cooling capacity. At the bottom, each column has been foreseen with electrical reboilers with 3 redundant resistors. The designed detritiation factor of the CDS was 20 when feeding the system with 320 mol/h of DT with a concentration of tritium of 3,939E-7 (at. fr.) during the first operational stage, keeping an inventory of T_2 in the entire system below 1.6g, required by the licensing regulations. Given that the new parameters differ from the designed parameters of the cascade, smaller feeding rate, different isotope concentrations, the evaluation of the system starts with a preliminary design for a distillation column based on the new gas compositions (table 1) and a flow rate of 26.78 mol/h (only case A is analyzed in this paper). The design is necessary in order to determine the feeding point of the gas stream that needs to be detritiated into the column cascade or, in other words, which column is fed first. The rule when choosing the feeding column is the similarity between parameters such as the reflux rate, number of theoretical stages of the newly designed column and the parameters of the columns from the cascade. Based on the obtained results, a reflux rate of 140 mol/h and the number of theoretical plates, 68, the feeding column for the new operating conditions is the third column of the cascade. In order to evaluate the performances and the operating parameters of the cascade in the new operating conditions, simulations have been done as shown in the following chapters.

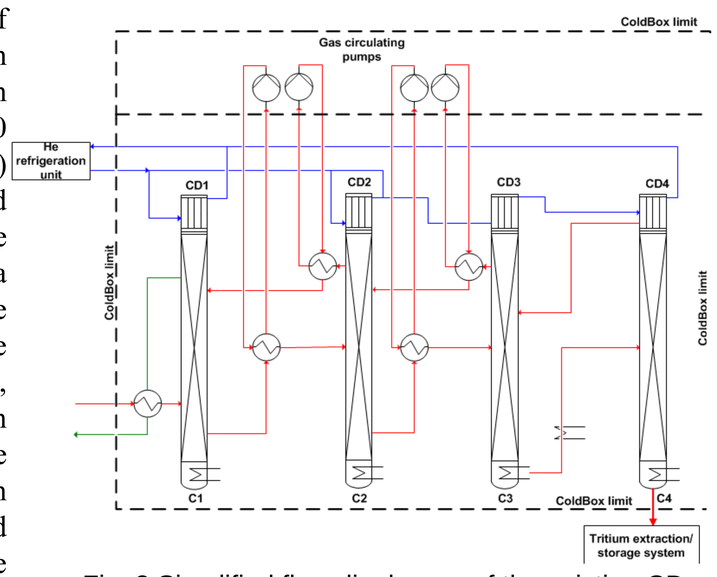

Fig. 2 Simplified flow diaphragm of the existing CD system

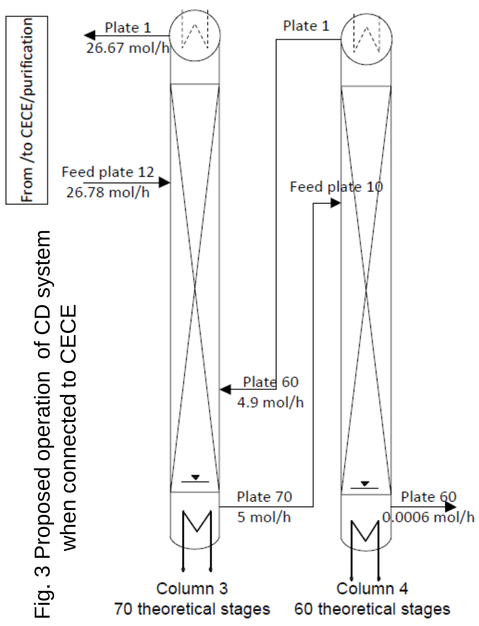

Fig. 3 Proposed operation of CD system when connected to CECE

Mathematical model of the cryogenic distillation process simulation

Material balance: $\sum_{k=2}^{j}(F_k - W_k - U_k) = L_i + U_1 + V_1 - V_{j+1}$

Component material balance: $(L_1 + U_1) * x_{i,1} = V_2 * y_{i,2} - V_1 * y_{i,1}$

$$L_{j-1} * x_{i,j-1} + V_{j+1} * y_{i,j+1} + F_j * z_{i,j} - (V_j + W_j) * y_{i,j} - (L_j + U_j) * x_{i,j} = 0$$

$$L_{N-1} * x_{i,N-1} + F_N * z_{i,N} - V_N * y_{i,N} - L_N * x_{i,N} = 0$$

Heat balance: $Q_j = q_j + L_{j-1} * h_{j-1} + V_{j+1} * H_{j+1} + F_j * H_{Fj} - (L_j + U_j) *_* h_j - (V_j + W_j) * H_j$

Gas feed composition when operation with CECE

	Case A	Case B
	mol fr.	
H_2	9.9970864e-01	9.6512142e-06
HD	2.8994787e-04	5.5792477e-03
HT	1.3771263e-06	3.6618089e-09
D_2	2.5927604e-08	9.9440965e-01
DT	2.7216558e-10	1.4424552e-06
T2	7.5026001E-13	5,4473214E-13

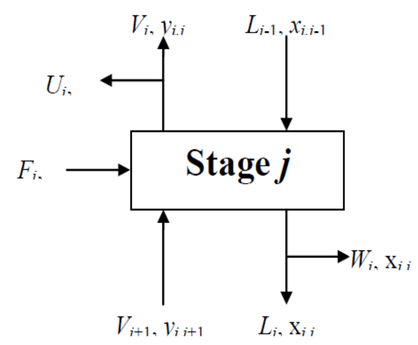

Fig. 4 Theoretical j^{th} stage

Simulation results and discussion

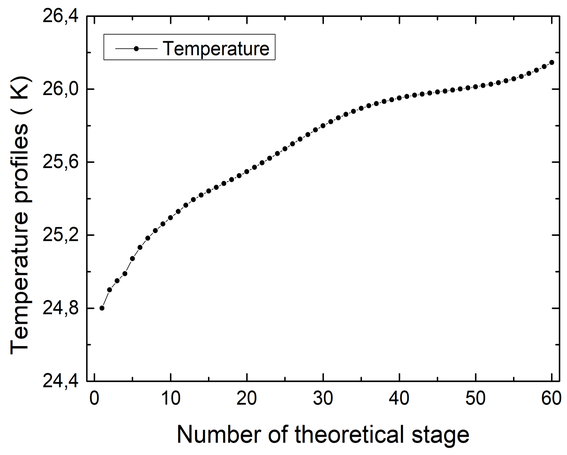

Fig. 5 Temperature profiles along the column 4

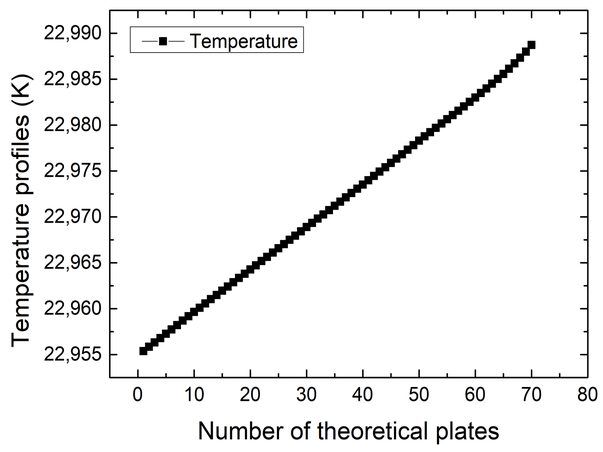

Fig. 6 Temperature profiles along the column 3

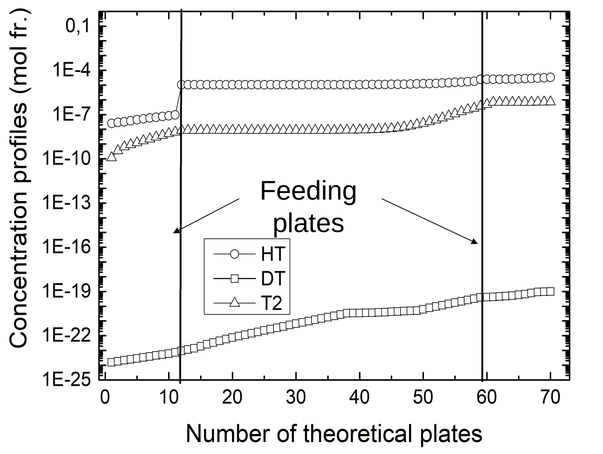

Fig. 7 Concentration profiles along the column 3

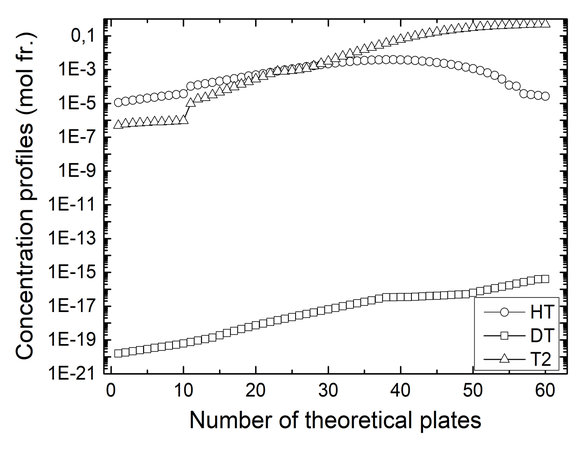

Fig. 8 Concentration profiles along the columns 4

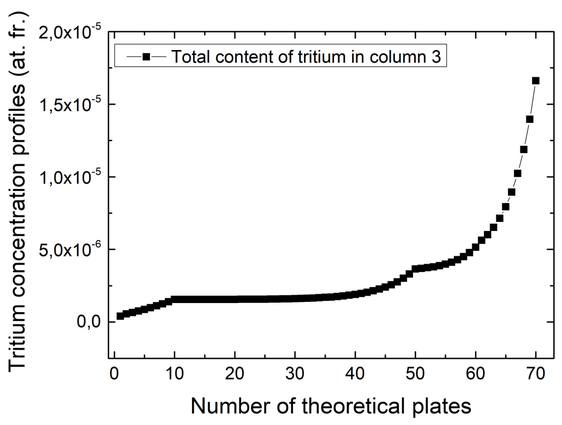

Fig. 9 Tritium profile along as-built column 3

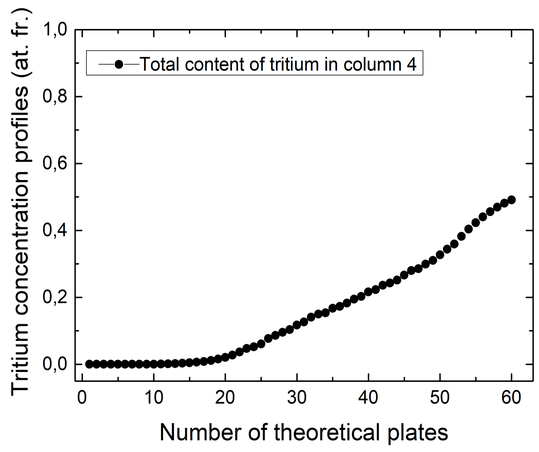

Fig. 10 Tritium profile along as-built column 4

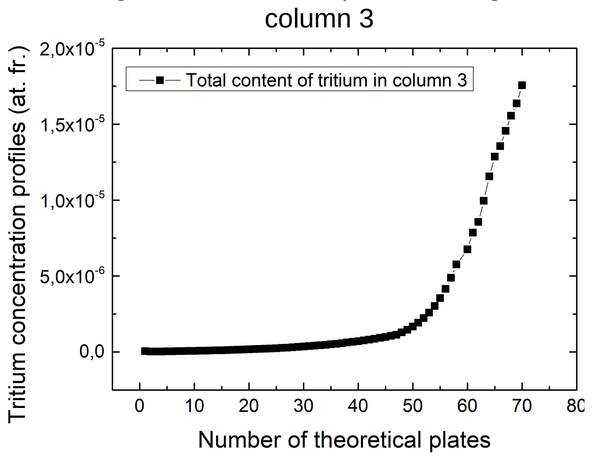

Fig. 11 Tritium profile along modified column 3

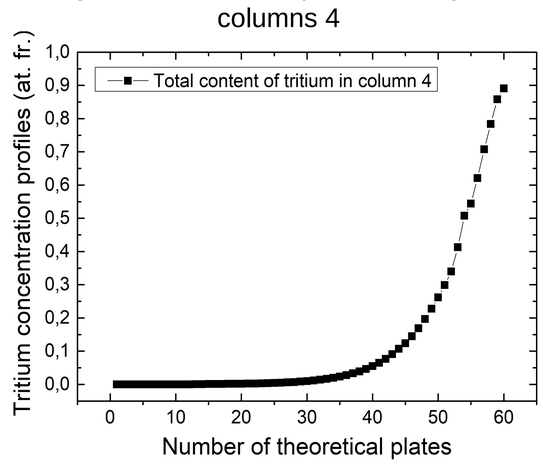

Fig. 12 Tritium profile along as-built column 4 (connected to modified column 3)

Conclusion

The analysis and simulations show that the cryogenic system can be partially used (columns 3 and 4) to recover and enrich tritium when connected to a CECE process for the given set of parameters. The detritiation factor reached for column 3 was 10 while tritium is enriched up to 50% in column 4. Fig. 11 and 12 show that if column 3 is modified and feeding is done to plate 50, tritium is enriched in column 4 up to 90%, while the detritiation factor increases to 23.