中国科学院理化技术研究所
Technical Institute of Physics and Chemistry, CAS

中国科学院空间功热转换技术重点实验室
Key Laboratory of Technology on Space Energy Conversion, CAS

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# Analysis and Tests of Hybrid Start-up Process of a Space Dilution Refrigeration Unit

**Zijie Pan[1], Lingjiao Wei[1*], Maowen Zheng[1*], Jingtao Liang[1,2], Shubao Zhao[1,2], Ziyao Liu[1], Jiarun Zou[1,2], Haowen Guo[1,2], Houlei Chen[1]**

[1] Key Laboratory of Technology on Space Energy Conversion, Technical Institute of Physics and Chemistry, Chinese Academy of Science, Beijing 100190, China
[2] University of Chinese Academy of Sciences, Beijing, China

## Abstract

The start-up process of the space dilution refrigeration unit with a high pre-cooling temperature are carefully analyzed and tested. The dilution unit starts successfully and obtains 162 mK at a flow rate of 4 mL/min $^3$He and 50 mL/min $^4$He. The operating conditions and the phase interface location are carefully discussed for the performance and optimization based on the experimental results.

## Space dilution unit

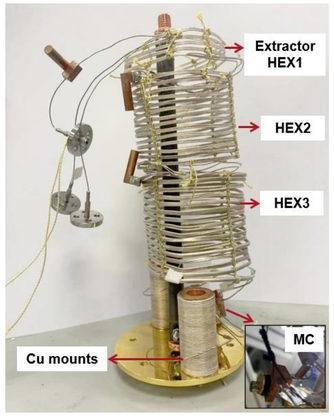


**Figure 1.** Space dilution unit

- The space dilution unit mainly consists of a series of capillary counter-flow heat exchangers (HEX) and a three-way mixing chamber (MC).
- **HEX1**: An extractor by accelerating the $^4$He speed higher than the supercritical speed to lock and extract the $^3$He.(L=1 m, d=40 μm)
- **HEX2/3**: The $^3$He injected is excess which produces 'droplets' in the return pipe to avoid the counter diffusion of $^3$He.(L=3 m, d= 200/400 μm)

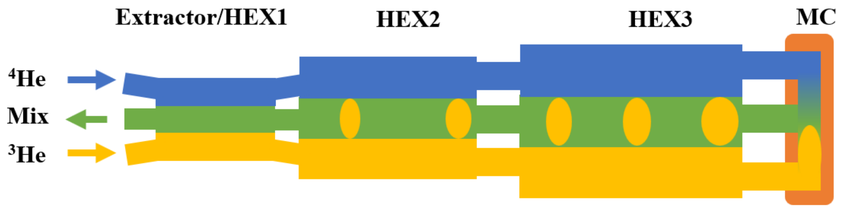


**Figure 2.** Schematic diagram of a space dilution unit

## Hybrid start-up principle and prediction

- Two types of the dilution process : direct dilution process ($\Delta\mu = 0$ ) and osmotic dilution process ($\Delta\mu \neq 0$ ).
- Direct dilution : depend on the excess enthalpy $H^E$ with a temperature limit of only 180 mK.
- Osmotic dilution : theoretically reach 0 K, depending on the osmotic enthalpy $H^{os}$. (need a superleak)
- The hybrid start-up process combines the two types and takes the direct dilution as the pre-cooling for the osmotic dilution.

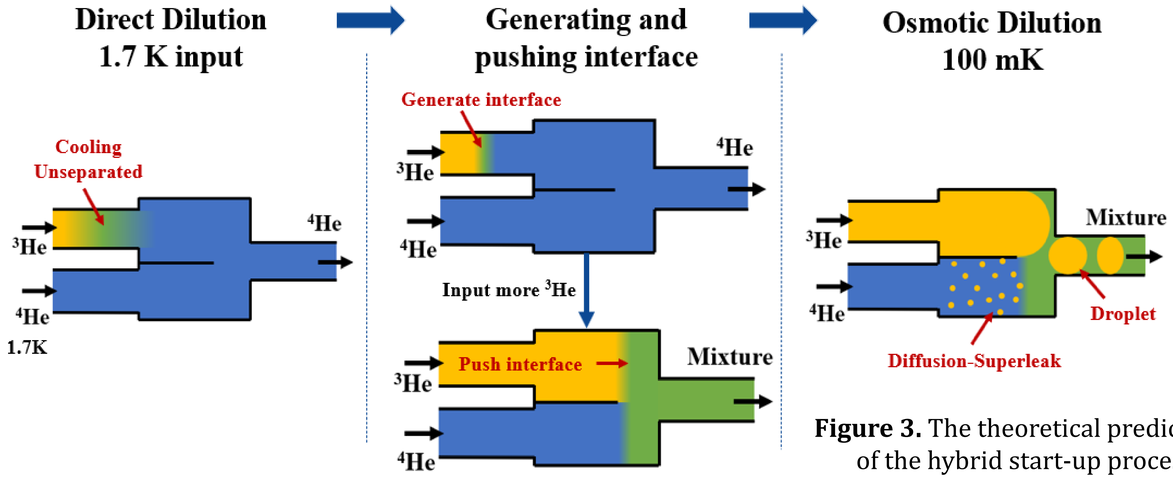


**Figure 3.** The theoretical predictions of the hybrid start-up process

## The start-up experiments

- $^3$He and $^4$He are injected at a $^3$He concentration of 17%at 1.2 K.
- ①**Direct Dilution**: $^3$He and $^4$He meet in the middle of the two-phase pipe.
- ②**Interface Formation**: reaches 590 mK, resulting in a stable phase interface.
- ③**Interface Shift**: the concentrated phase begins to push the phase interface to the MC with more $^3$He input, where $T_{mc}$ drops sharply to 480 mK.
- ④**Osmotic Dilution**: $T_{mc}$ keeps declining and approaches 178 mK (<180 mK). This indicates that direct dilution process changes to osmotic dilution process.

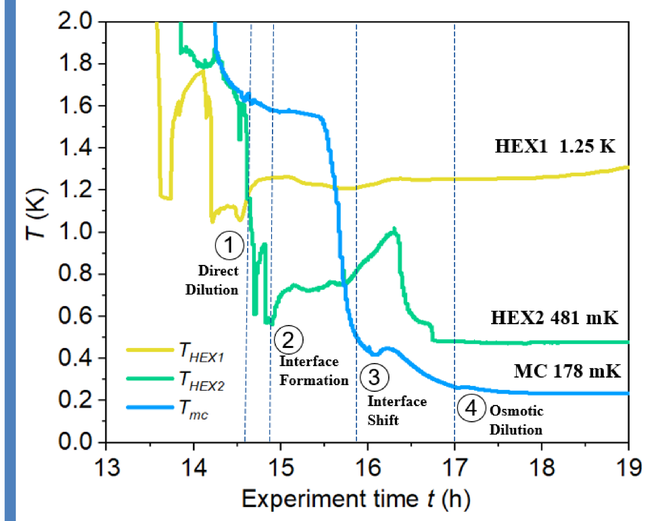


**Figure 4.** The hybrid start-up process

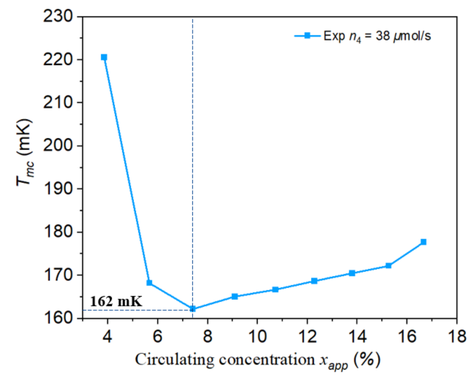


**Figure 5.** Circulation concentrations experiments

- $x_{app}$: 17%→7%, $T_{mc}$ decreases to 162 mK.
- $x_{app}$: 7%→3.8%, it causes damage to the phase interface.

## Conclusion

- The dilution unit successfully starts at 1.2 K and ultimately reaches 162 mK.
- The hybrid start-up experimental results are highly consistent with the theoretical predictions.
- The damage to the phase interface caused by insufficient $^3$He proves evident in the experiment.