Development of a forced-convection gas target for improved thermal performance

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Introduction

The internal pressure experienced by a gas target during irradiation is dependent on the beam energy deposited in the target, the beam current, and the thermal behaviour of the target [1]. The maximum beam energy deposited is a function of the cyclotron capabilities and the gas inventory within the target and is limited by the pressure produced in the target and the ability of the target assembly to remain intact. This is also a function of the thermal behaviour of the target, which is difficult to predict a priori since it is dependent on such things as convection currents that occur during irradiation. We conducted bench tests with model gas targets with and without forced convection currents to observe the effect on thermal behaviour. Based on those results we constructed a prototype gas target, suitable for irradiation, with an internal fan assembly that is rotated via external magnets.

Material and Methods

Bench tests were conducted with a conical target body made out of aluminum. A nickel-chromium heater wire was inserted into the gas volume through the normal beam entrance port (FIG. 1) to heat the gas while water cooling was applied to the target body. The voltage and current of the heater coil was monitored along with the pressure inside the target and the water inlet and outlet temperature. In the case of tests with a driven fan blade either the voltage applied to the electric motor was monitored or the fan speed itself was recorded. By assuming the ideal gas law, the pressure gives the average bulk temperature and a global heat transfer coefficient can be calculated between the target gas and the cooling water [2]

As the bench test target employed a simple o-ring seal on the rotating shaft, it was not robust enough for any tests under beam conditions. Therefore, a prototype design suitable for in-beam operation employs a propeller mounted on a rotating disc housing two samarium cobalt magnets and spinning on two micro-bearings which are constructed to operate in high temperature environments. The micro-bearings are mounted on a pin projecting from a plate mounted to the back of the gas target to allow assembly of the fan mechanism prior to attachment to the body (FIG. 2).

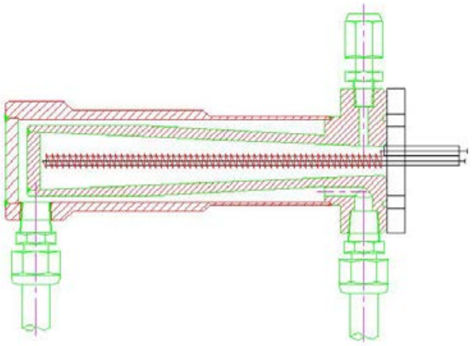

Figure 1: Cross-section of typical gas target with heating jig inserted. Jig mounts where entrance foil is normally mounted. Inner volume is target gas pressure vessel, outer volume is water cooling jacket.

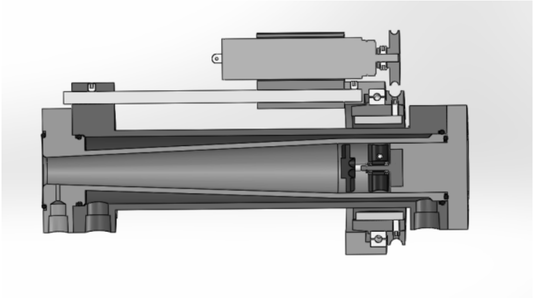

Figure 2: Cross-section view of prototype fan target. Beam enters from left with fan assembly at the back of the target. The fan assembly can be removed for inspection or modification.

The target body was again aluminum. Other materials were selected based on their chemical inertness and minimal activation, though it is not intended that beam will strike the fan assembly. No carbon-containing metals or alloys were used, and no lubrication of any kind was employed on the internal propeller assembly. The rotating disk inside is driven by an outside rotating ring also equipped with rare-earth magnets. The fan speed was recorded with reed switches measuring the rotational frequency of the magnets. Different propeller shapes were tested with smoke in a glass tube and the final propeller was optimized for maximum turbulence along the beam propagation.

[^{11}C]CH$_4$ yields were measured after irradiation with a 20 µA proton beam of nitrogen gas (with 10% hydrogen) with a fill pressure of 300

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psig. The irradiated gas was directed over a Porapak trap cooled in liquid nitrogen. The valves on the entrance and exit of the trap were then closed and the trap was inserted into an ionization chamber calibrated for ^{11}C. The trap was then cooled again. In this fashion, three yield measurements were performed for each irradiation at different time points after end of bombardment (EOB). All yield measurements were decay corrected to EOB and averaged over each run.

Results and Conclusion

In the bench test operation the fan (about 10,000 rpm) made a dramatic difference in the pressure rise inside the target. A simple aluminum cylindrical target filled to 300 psig with ~400 W of heat applied rises to only 400 psig with the fan operating versus 600 psig without, see FIG. 3.

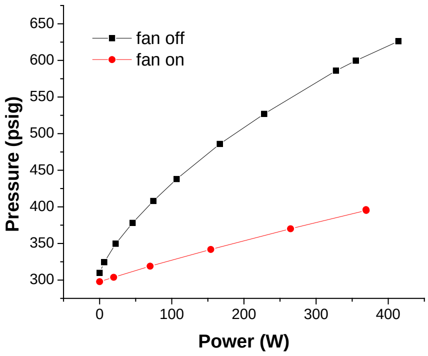

Figure 3: Pressure rise as a function of heater power in a cylindrical aluminum target filled with nitrogen to 300 psig.

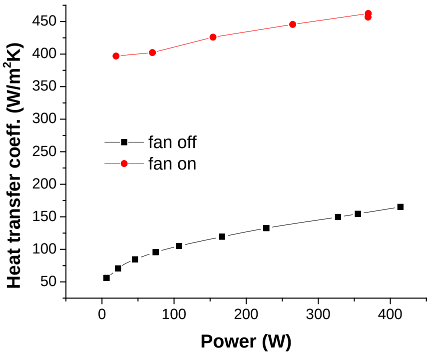

Figure 4: Impact on global heat transfer coefficient of natural versus forced convection caused by internal heating.

The effect of increased natural convection currents to the overall heat transfer rate as the heat load is increased is seen in FIG. 4. The natural convection currents (fan off) increase with the heating of the gas and presumably improve the thermal behaviour due to increased mixing and a thinning of the stagnant layer of gas on the walls of the target. Operation of the fan results in a large increase in the heat transfer coefficient but the trend of an increased heat transfer rate with increasing power is still observed.

The prototype for irradiation was commissioned at the TR13 cyclotron with argon gas and nitrogen gas (with 10% hydrogen). This target has currently a slower fan speed than the bench-test version, only in the order of 1000 rpm. The target valves and pressure transducer are installed about two meters away from the target body, outside of the cyclotron shielding and connected via a 1.6 mm inner diameter stainless steel line. This long line results in additional dead volume, quite in contrast to the bench test target which had the target valves mounted close to the body. Consequently, a smaller pressure difference between fan-off and fan-on operation during irradiation is observed, see FIG. 5, but it appears that with higher fan speed a higher pressure difference could be possible.

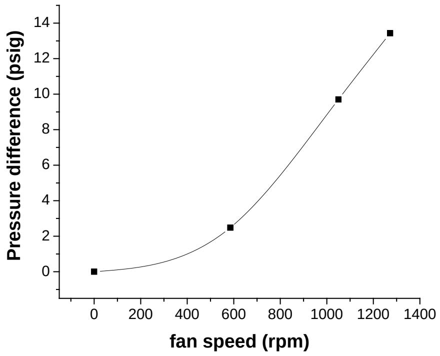

Figure 5: Dependence on fan speed of the pressure difference between fan-on and fan-off operation during irradiation. Irradiation conditions are 20 µA beam current at 13 MeV beam energy and 300 psig of fill pressure.

Given the small pressure difference, the heat transfer coefficient does not increase as dramatically with forced convection in the irradiated target as it did inside the target with internal heating, see FIG.6.

The very preliminary yield results for different irradiation lengths can be seen in FIG. 7. So far, only one measurement per irradiation duration has been performed. Within the limited statistics, the increase in the saturation yield A_{sat} due to the fan operation ranges from 20% for a

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5 minute irradiation to 57% for a 40 minute irradiation. Fitting the formula

$$Yield = A_{sat} \cdot I \cdot e^{-a \cdot t} \cdot (1-e^{-ln2 \cdot t/t\_1/2})$$

according to [4] results in A_{sat}=71.8±0.5 and a=0.0072±0.003 for the fan-on operation and A_{sat}=64±2 and a=0.016±0.001 for the fan-off operation, suggesting that the fan is indeed affecting the target performance.

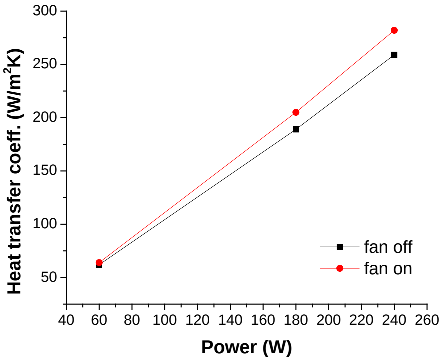

Figure 6: Impact on global heat transfer coefficient of natural versus forced convection during irradiation.

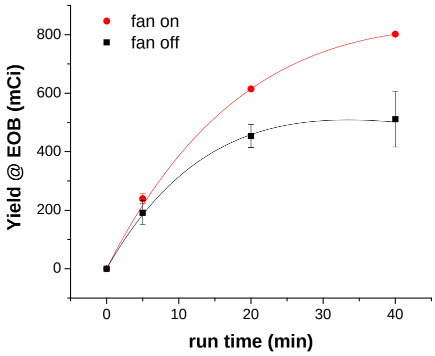

Figure 7: Yield at EOB for 20 µA beam current at 13 MeV beam energy and 300 psig of fill pressure (~ 410 psig during irradiation) and a fan speed of 1000 rpm. Only one irradiation was performed for each data point. The solid line is a fit according to [4].

We have demonstrated that the fan operation in a gas target does influence the pressure during heating whether that is via a heating coil or by proton beam irradiation. Fan operation may affect the produced yield of $[^{11}C]CH_4$, although the limited irradiation conditions tested and the limited statistics of the yield measurements must be interpreted cautiously. Further experiments, including different fill pressures and the production of $[^{11}C]CO_2$ are required to determine the mechanism caused by the fan operation that may increase the yield of $[^{11}C]CH_{4.\ psi}$

References

1. D.J.Schlyer: http://wttc.triumf.ca/pdf/2004/Tutorial%20pdf/DJSchlyer_WTTC.pdf
2. J.P. Holman: Heat Transfer, 9th Edition, Mcgraw-Hill College, 2002.
3. K.R. Buckley: US Patent 8249211, 2012.
4. K.R. Buckley, S. Jivan, T.J. Ruth, Nuc. Med. Biol. **31**, 825-827, 2004.

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