Shape optimization of Herschel small nozzles towards a smaller plume divergence

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Herschel satellite uses helium to cool scientific instruments down to temperatures of 0.3 K. Helium is continuously released through small nozzles and these nozzles create a counter-torque to compensate torque caused by the solar pressure acting on satellite surfaces. Plumes exhausted from the nozzles impinge on the satellite surface and this leads to generation of disturbing forces and moments that can decrease life-time of the Herschel satellite, significantly. Therefore, the nozzle design shall minimize the impingement effects. A mass flow rate through the nozzle is very small and, as a result, a gas flow inside the nozzle is in transitional flow regime. In this case friction force plays much more important role than it does in a continuum flow regime. This leads, for example, to a formation of rather thick boundary layer and wider plume and an optimal nozzle shape differs from a shape predicted with the continuum flow approach. There are studies dedicated to optimize nozzle shapes and to provide a higher nozzle performance (e.g. thrust and specific impulse) in the viscous flow regime. However, plume divergence for low-Reynolds number nozzle is a new task that was not addressed in transitional flow regime. A numerical analysis showed that the initial design of the Herschel small nozzles created a wider plume than it was anticipated.

The paper presents a numerical analysis of nozzle and plume flows aimed to optimization of the nozzle shape and decrease of the plume divergence. The computations were performed with a kinetic approach (the direct simulation Monte Carlo method) for different shapes of subsonic and supersonic nozzle parts taking into account restrictions on the nozzle geometry. For example, the nozzle shall be manufactured using the conventional technologies and there are restrictions on maximum values for nozzle length and diameter. It was shown that a half-angle of the supersonic part affects the plume divergence more significantly than other key parameters: shape of the subsonic part, throat, expansion ratio, and nozzle lip shape. As a result of computational analysis, the nozzle shape was chosen and experimental testing of the new nozzles confirmed the numerical prediction on mass flow rate. The optimized nozzles have been installed on Herschel satellite.

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