written as

$$\left(\frac{\partial Q'}{\partial t} - H'\right) A + \sum_{i=1}^{4} [(E - E_v)'_i C_x + (F - F_v)'_i C_y] = 0 \tag{20}$$

where

$$\begin{aligned} Q' &= \bar{y}Q \\ H' &= \hat{y}H \\ (E - E_v)' &= \bar{y}(E - E_v) \\ (F - F_v)' &= \bar{y}(F - F_v) \end{aligned} \tag{21}$$

It is clear that $A$ and $C$ are the cross-sectional AREA and the boundary LENGTH, respectively, of a control volume in a two-dimensional, curvilinear coordinate system.

The above discussion shows that the discretized flow equations in a two-dimensional, curvilinear coordinate system can be easily transformed to the axisymmetric system with the following steps:

1) Multiply the time marching term by the radial coordinate of the control volume centroid $\hat{y}$.
2) Reformulate the divergence of the velocity vector according to Eq. (9).
3) Multiply the flux terms with the radial coordinate of the boundary centroid $\bar{y}$.
4) Add the source term [due to the axisymmetric coordinate, Eq. (4)], multiplied by the radial coordinate of the control volume centroid $\hat{y}$ to the radial momentum equation.

## Concluding Remarks

The axisymmetric flow equations have been organized in a vector form suitable for CFD applications. The physical meaning of the source term in the radial momentum equation due to the axisymmetric coordinate system is discussed. The details of the volumetric and surface integrations for a single cell are examined. A convenient method of modifying existing two-dimensional codes to axisymmetric ones is proposed. Most importantly, no numerical accuracy has been sacrificed in calculating the volume and surface areas of the control volume with this method.

## Reference

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# Technical Comments

## Comment on "Propellant Production from the Martian Atmosphere"

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THE topic treated in the Note is fascinating. But I feel that the figures quoted are very optimistic.

Believing that 3.61 kWh suffice to produce 1 kg of propellant liquids, then the photocell area required on Mars surface (not movable, flat on surface, near equator) for production of 13 t propellant per (Earth) year would come to 600 $m^2$ with space-type photocells of today; a solar dynamic plant with a steerable parabolic mirror might require 13-m receiver diameter.

For a Hohmann-type manned Mars mission, this might be quite attractive; obviously, the first manned exploration could use this only if proper verification were available from prior unmanned Mars missions. Since I don't think this likely, maybe this plan is rather for growth potential for later manned flights, if the first one proved operationability!

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## Reply by the Authors to H. O. Ruppe

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IN the Note,[1] the calculations of propellant production using the electrical power from a 100-$m^2$ solar-cell array were done approximately with information available at the time. This was justified because the central topic of the note was the determination of the specific impulses of the carbon monoxide and liquid oxygen mixture, and not the propellant production. In response to Ruppe's comments, we have redone the propellant production calculations. We found that our original production value of 13,000 kg of propellants in one Earth year from a 100-$m^2$ solar panel was too optimistic, but certainly not by a factor of six. A brief review of our principle assumptions and the revised calculations follows.

Our assumption that a 20% solar cell efficiency can be realized in the next two decades was probably conservative.

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Presently, silicon solar cells have an efficiency[2] of 17%, and gallium arsenide of 18–19% at the low temperatures of 220–235 K measured on the Martian surface.[3] However, we neglected solar energy absorption and scattering by the thin Martian atmosphere which has a ground-level pressure[3] of only about 6.5 mb. Recent calculations[2] predict about a 20% attenuation of solar flux on a clear day (optical depth of 0.5).

The electrical energy produced by a flat panel, on a clear day near the Martian equator, is[2] about 730 W-h/day m$^2$ using 17% efficient solar cells. For solar cells with a 20% efficiency, the energy becomes 860 W-h/day m$^2$. Therefore, a 100 m$^2$ panel can produce $1.13 \times 10^5$ MJ in one Earth year. However, if sun tracking is used, the energy output is increased by $(2)^{0.5}$ to $1.60 \times 10^5$ MJ.

The above values are optimistic because the effects of dust storms are neglected. Global dust storms have been observed on Mars an average of one every 3.8 Earth years during the past 35 yr.[4] About three months are required for the dust to settle out of the atmosphere.[5,6] Therefore, atmospheric dust from global storms was present about 7% of the time. The Viking Mars landers observed a maximum increase of the optical depth to four during global dust storms. If we assume an average optical depth of 2.2 during the 3 months-long dust settling period, the energy output[2] is reduced by about 30% and the average annual output is decreased by 5%. However, local dust storms occur also. Local storms are more frequent, but last for much shorter times than global ones. Therefore, we will reduce the average energy output due to atmospheric dust by a total of 10%. Thus, the solar panel areas that would be required to generate the electrical power that is needed to produce 13,000 kg of propellants[1] (at 13 MJ/kg) are 165 m$^2$ for a flat stationary one, and 115 m$^2$ for a sun-tracker. Even when an additional increase in area is added to provide a contingency factor (the determination of which is well beyond the scope of this analysis), the above areas would be far less than Ruppe's 600 m$^2$.

Naturally, a propellant production facility would either have to be operational at Mars before a manned vehicle would be launched from Earth, or it could be used to provide propellants for portions of subsequent missions as suggested by Ruppe. However, using a Hohmann-type of interplanetary trajectory is highly undesirable because the long trip times would expose the crew to dangerous doses of cosmic radiation and solar flares. Other trajectories having modest energy requirements, but offering much shorter trip times, have been identified.[7]

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