Galvanizing on the Moon
An essay
with new problems & solutions found every week

Dubois Michel

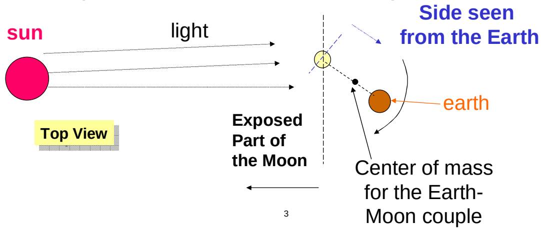
An exercise which looks funny but which is not and rises questions

A Not so easy simple Task

Come Back to Basics

Far Side - Near Side – Dark Side

- Moon side facing the Earth is the near side, & the opposite side the far side.
- Far side should not be confused with Dark side, the hemisphere that is not being illuminated by Sun at a given moment
- The day on the Moon last 27.3 earth days



What makes the difference on the Moon?

- **Lower Gravity: 1/6 of earth value**
  - G is only 1.62m/sec²
  - Lower weights but same mass
  - Buoyancy effect is reduced
- **Different Temperatures**
  - Sunlit side : ~110℃
    - *Water is boiling (enhanced by low atmosphere pressure)*
    - *Expected problems with electrical equipment*
    - *Could be decrease by shelter but T closer to dark side*
  - Dark Side : ~-170℃
    - *Water is solid*
    - *Beware of Steel brittleness*

…..Don't forget that the near side (facing the earth) and the far side (never seen from the earth) are both exposed to sun at a given moment

- *Beware of Strong thermal expansion*

What makes the difference on the Moon?

- **No atmosphere:**
  - Pressure only 10^{-12} bar (day) 10^{-15} bar (night)
  - Just a few He(20%), Ne(23%), H_2(17%) and Ar(16%vol)
  - Heat transfer by Convection cannot be used
  - Very low Oxygen (exact level not well known)
    - *No combustion possible*
    - *No Fe oxidation*
- **Low Pressure**
  - Impact on fluid mechanics of gas knife
  - Oil, Water, Zn evaporate easily
- **Cosmic Radiation**
- **Direct Radiation from Sun**
  - Equipment will be hit by high energy particle

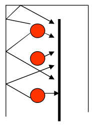
A Limited analysis

Whereas Hot Dip Galvanizing include many different processes, only some of them are adressed

- Incoming Coils
- Cleaning
- **Annealing & surface preparation**
- **Zinc Coating**
- **Final Cooling**
- SKP
- Oil
- Defects
- Operators
- Energy

Annealing

- No change in the target peak T
- Combustion is too expensive due to no O_2
- Electric heating is easy
  - Photo cells for electricity production
  - Radiative heating by Resistance
  - Furnace casing required to improve radiative heat transfer
    - *Use of reflection*
    - *But the casing may be open*
  - ... or possible use of Resistance with integrated reflector like UV or IR baking
  - No Heat loss by natural cooling

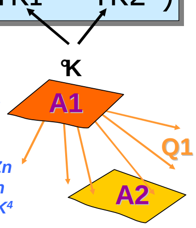


- Induction with longitudinal flux limited to ~650°C
  - Use of Transverse flux OK, but edge management is not easy
- No need of protective atmosphere against oxidation

The Basics of Radiative Heat transfer

- Exchange between 2 surfaces
  - Heat exchanged by A1

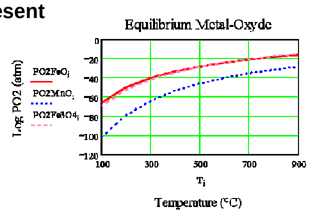
$$Q12 = A1 * \varepsilon * c0 * F12 * (TK1^4 - TK2^4)$$



- With
  - *F = shape factor: good in cooling tower*
  - *A1 =emitting surface*
  - *T = Temperature: quite low after Pot*
  - *ε = surface emissivity: ~0.05 for liquid Zn*
  - *~0.12 for solid Zn*
  - *C0 =Boltzman Constant: 5.67E-8 W/m²/K⁴*

Surface Preparation

- No need of H_2 for reduction... if cold rolled on the moon
  - Not so clear if rolled on the earth: 100nm oxide-hydroxide present



- $PO_2 < 10^{-60}$ at 500°C to FeO -> Fe + 1/2 O_2
- If Pmoon = 10^{-15}, Oxygen concentration is low
  - *Maybe low PO_2 reached*
  - *High T° will help kinetics of spontaneous reduction*

Surface preparation

- Strictly: No need of N_2 for protective gas
  - No oxidant is present
- But Surface Segregation will occur by Gibbs Segregation
  - All elements moving to grain boundary will enrich the surface in Vacuum annealing
    - *The Grain boudary is an Oxygen free zone with lots of voids*
  - Risk of Carbon, P, S, Sb, Sn covering the surface
    - *Changes of wettability*
    - *Carbon will help oxide reduction in solid state on High Carbon steel*
    - *Risk to form spangles in a Pb-Sb free bath*
  - Surface enrichment may change the Fe-Zn reaction

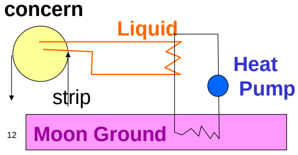
Cooling before the Coating

- Much more difficult because forced convective gas cooling cannot be used
- Radiative cooling is too slow
  - Strip emissivity is not high: typically 0.2

EqEm 800°C=0.213 Max 15kW/m²/side	EqEm 500°C=0.174 Max 13kW/m²
→ 74kW/m²/side	→ 55kW/m²/side

Cooling before Coating

- Possibility to use Phase transformation
  - Liquid evaporation or sublimation on the sheet
    - *Ex CO2 (not available on Moon), Ne....*
  - Need to obtain liquid either by cooling or from earth
  - Low pressure means spontaneous evaporation of sprays & Drops
- Re-consider the Roll Quench system
  - Known that this process induce flatness concerns due to variation of heat transfer with contact force
  - Cooling the roll is still a concern
    - *Gas cooling... H2, He*
    - *Pressurized Water cooling*



Pressure in the Box & Convection

- Higher Pressure increases Gas consumption
- Low Pressure may impact Heat transfer
- Typically for Forced Convection

$$Nu = f(\mathrm{Re}, \mathrm{Pr}, Design)$$

$Nu = h * \frac{Dimension}{Conductib}$ $\mathrm{Re} = \frac{Velocity * Dimension * \rho}{\mu}$ $\mathrm{Pr} = \mu * \frac{Cp}{Conduct}$

Ø From Practice & Theory
- *Cp, μ_{gas} and gas conductibility only depends on T….except perhaps at very low Pressures*

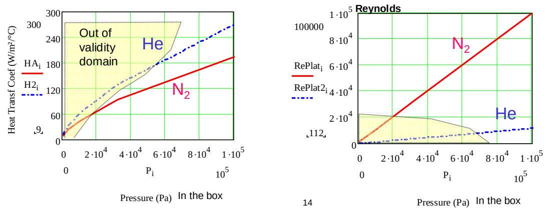
Ø Correlations Nu=f(Re, Pr, Geometry) are still valid
- *But keep in mind their validity domain, especially Re*

Pressure in the Box & Convection

- Effect of Pressure in only on Density
  - Ø Re decreases with Pressure

$Nu = h * \frac{Dimension}{Conductib}$ $\mathrm{Re} = \frac{Velocity * Dimension * \rho}{\mu}$ $\mathrm{Pr} = \mu * \frac{Cp}{Conduct}$

Prediction of h Slot Type: Gap 7mm, Pitch 300mm, Dist 125mm, Gas vel=130m/sec
Martin Correlations



Pressure in Box & Gas Consumption

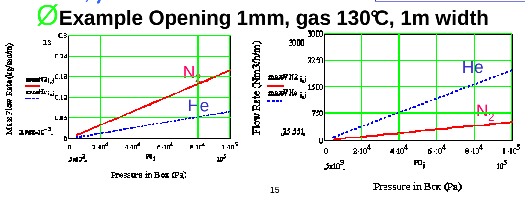
- The Max Gas flow is defined by

$$mMax(\gamma, R, TT0, PP0) := d \cdot \sqrt{\frac{\gamma}{R \cdot TT0}} \cdot PP0 \cdot \left(\frac{2}{\gamma+1}\right)^{\frac{(\gamma+1)}{2\cdot(\gamma-1)}}$$

- *In kg/sec*
- *PP0, TT0= static P,T in the bow*
- *d=opening*
- *R, γ= Gas constant*

Helium	N2
$\gamma He := 1.65$	$\gamma N2 := 1.4$
$RHe := 2079$	$RN2 := 296.8$

Ø Example Opening 1mm, gas 130°C, 1m width



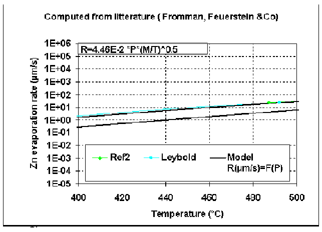
Furnace Design Summary

- A furnace under Pressure seems the best
  - Ø Because of cooling
  - Ø To minimize the number of Seals
    - *Sonic flow at seals*
  - Ø Probably use of He under 0.4atm
    - *Available in the environment*
    - *Good thermal efficiency*
    - *Risk of Gibbs segregations*
- Heat recovery from cooling to obtain heat at the entry
- Electrical heating supplied by Photo cells

Zn Pot

- Zn evaporation from the pot is expected Huge
  - Ø No Oxide on the surface to impede evaporation
  - Ø About 5-10µm/sec at 460°C/sec
    - *Explained by the High Vapour Pressure of Zn*

But evaporation consume heat: 56J/gr … reduce T



Zn Pot

- 1µm Zn lost/sec: ~7g/m²/sec a huge value
  - Ø About 1500kg/h for a usual pot (12m², 5µm/sec)
  - Ø Consume ~23KWh only for evaporation + 120KWh for heat & melt
  - Ø Benefit for the Zn vapour deposition process
  - Ø A Nightmare for Zn Yield of Galvanizer
- Dross decantation expected lower
  - Ø Zn viscosity identical
  - Ø Buoyancy force decreased by 6 times
    - *6500-4500 kg/m³ for Zn & Dross*
      Up force is only 1/6 on the moon
    - *The Dross problem is not going to improve*
      - Same Fe dissolution
      - Same Zn Viscosity
      - Lower Buoyancy force
      - Higher Fe content in melt

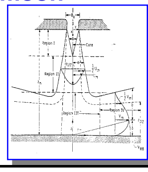
$$Vdec = (rFe2Al5)^2 \cdot (\rho Zn - \rho Fe2Al5) \cdot \frac{g}{\mu Zn} \cdot \frac{2}{9}$$

Reaching the Coating Weight

- The Final coating weight is the result of External forces
  - Entrainment by viscosity
    - *No change expected*
  - Application of external forces
    - *Typically P gradient and Shear Forces in Wiping in atmosphere*
  - Gravity is predicted to have no effect on the Final coating weight
    - *Due to the much higher effect of knife forces*

Wiping

- Present prediction based on Navier Stokes equations can be used because the Zn layer is continuous
- Any type of Forces can be applied in wiping models
  - Magnetic Wiping never succeeded on earth
    - *Heating problems*
    - *Edges management*
- ⇒ No change expected on the moon
  - Gas Wiping
    - *Need full re-analysis because P shape depends on Navier Stokes*

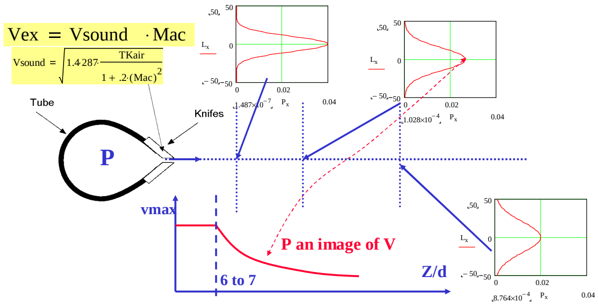


Gas Wiping

- In atmosphere, Gas Velocities decrease due to Viscous entrainment

$$Vex = Vsound \cdot Mac$$

$$Vsound = \sqrt{1.4 \cdot 287 \cdot \frac{TKair}{1 + .2 \cdot (Mac)^2}}$$



Gas Wiping

- In Vacuum, situations are different
  - No viscous entrainment of ambiance

$$PGradien_{i,j} = BB \cdot \frac{\rho gas}{2} \cdot (Vgas_{i,j})^2 \cdot d \cdot (\ldots$$

$$Shear = -CC \cdot \frac{\rho gas}{2} \cdot (Vgas)^2 \cdot d \cdot (\ldots$$

NOT Valid because gas velocity is no more Gaussian Shape

At nozzle exit

BB, CC= Constant
d= nozzle opening
Z= distance

  - Exit Velocities are expected much over Sound speed….
    - *shock waves cannot be avoided due to the very low pressure on the moon*

Gas Dynamics & Temperature

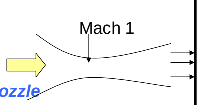
- Gas speed is defined by the Compressive Expansion Law
  - In Vacuum, the Max velocity is defined by

$$V\,max = \sqrt{\left(\frac{2*\gamma}{\gamma-1}\right) * \frac{R}{M} * Tgas}$$

M=Molar mass
R= gas constant

which correspond to all gas energy transformed into velocity

- *Example:*
  - *TN_2=350K Velocity= 852m/sec much higher than sound velocity*
- The Max Velocity requires
  - *Perfectly adapted Converging Diverging Nozzle*
    - Not possible on the moon due to the very low pressure
    - Shape should be adjusted with Wiping P
    - Not possible to avoid Shock waves



Gas jet on the Moon

- The Wiping Force is the Pressure Gradient
  - How does it develop with:
    - *A choked gas flow with shock waves*
    - *An expansion in Vacuum without viscous entrainment coming*
- The interaction Gas Liquid Zn must be reanalyzed
  - The Pressures on the sheet must be recomputed
  - Shear stresses are expected very different

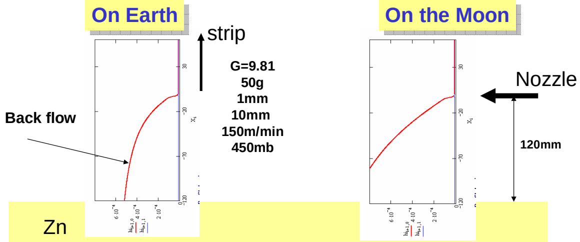
A Whole New World is Coming

- But a Final solution will exist for NOISE
  - No media for Pressure waves transportation

And what is the effect of Gravity

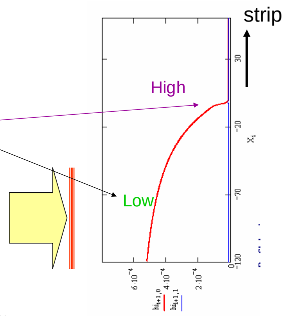
- Gravity impacts the total Film Thickness profile under the knives
- But Gravity has no effect of the final coating weight because of high wiping force

On Earth | On the Moon



And what is the effect of Gravity

- Explanation
  - The film thickness at any location is the result of
    - *Viscous entrainment*
    - *External forces*
      - Pressure Gradient
      - Shear forces
      - Gravity… constant
  - Gravity can only impact the film where other forces are low



And what about Zn Evaporation

- Between Pot and Wiping: No impact
  - Residence time only 0.2 to 0.15 sec
  - Eventual Zn loss cannot impact the final coating weight
    - *Prewiping cannot work*
- After wiping is critical
  - Time in liquid state depends on cooling rate after wiping
  - Typically 6-8sec on a 1mm thickness
    - *Loss of 6µm by evaporation (avg 440℃)*
    - *Much more in practice due to difficulties in cooling*
    - *Need to adapt coating weight at Nozzle with Solidification time… but thin coating are easy to reach (20g/m² at 180m/min)*

Wiping with a Reactive Gas may be mandatory

Cooling Tower

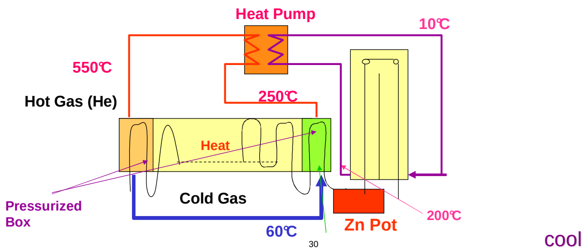
- The most difficult process
  - Convection cooling is not possible … except under atmosphere
- Only radiation is possible
  - But Zn emissivity is low as well as Temperature
- Not Possible to Cool quickly
  - Very high tower expected
  - But no vibration induced by cooling
    - *No gas impingement*
  - Ga has advantage on Gi with a higher emissivity
  - GL will become very critical due to higher T
- Water quench has the same concern
  - Full evaporation of liquid water due to low Pressure

The Cooling Tower On the Moon

- Cooling Liquid & Solidified Zn is a nightmare
  - Zn emissivity cannot be changed
    - *No change to increase radiation*
  - Make a Closed box with atmosphere???
  - High Tower to increase time…. may be the solution
    - *No earthquake*
    - *No wind*
    - *Low gravity decrease foundation strength*
    - *No need of Sidings for the building*
      - No sound propagation
      - No dust, no flies and mosquitoes
      - No competitors to watch our process
    - *But beware of Sun radiations during day and meteorite drops*
    - *Beware of strong T° variations inducing Thermal Expa nsion*

The Cooling Tower

- A possible solution
  - Closed tower with atmosphere and recover heat on the strip by heat pump (or Peltier cell)
  - Helium could be used for efficiency and avoid Water quench water



Conclusion

- Galvanizing on the Moon is not an easy Task but a good challenge for R&D
  - Cooling is a nightmare
    - *In the furnace*
    - *In the tower*
  - ..Implying the necessity to work with atmosphere
    - *Any finally the use of expensive seals*
  - Zn Vaporizes Hugely
    - *In the Pot*
    - *After wiping*
  - Zn Wiping by gas jet must be completely re-analyzed
    - *The behaviour of the gas jet is different in Vacuum*
  - Wet SKP must be analysed

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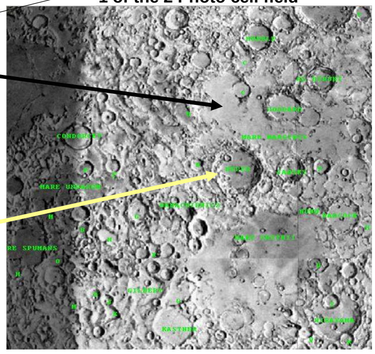
And Where on the Moon?

- Watch for a Site

1 of the 2 Photo cell field

Flat and close



In craters may have some advantages Less exposed to sun

Or Where Else?

- And what about Venus
  - Strong atmosphere is available
  - CO_2 is for Free
  - 450℃ all the time… lot of energy saving
  - 80bar … good for Zn vaporization
- But
  - How to avoid Galvannealing …. reaching only a Fe-Zn strip…. Very brittle
  - Ageing after SKP cannot be avoided
  - …
- Think about the new Exo Earth?

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Conclusion

- Galvanizing on Earth is a Must
  - Oxidizing atmosphere has more advantages than drawbacks
  - Lower gravity has no real Benefits
  - Life would not be funny because of the difficulty to organize friendly Barbecues due to lack of Oxygen

Take care of our Planet !