Excess Liquid Formation in Orbit Test Results of Axially Grooved Heat Pipes

R. Meyer,* U. Laux,* and R. Schlitt*
MBB/ERNO Raumfahrttechnik GmbH, Bremen, Federal Republic of Germany

A heat pipe flight experiment on SPAS 01 was performed in February 1984 to investigate the function of excess liquid within heat pipes. The pipes were to be used for the Franco-German direct broadcasting satellite TV-SAT/TDF-1. The aim of the experiment was to prove the hypothesis that slug formation represents the more stable configuration contrary to film formation in 0-*g* conditions. Computer models had been developed to derive the slug formation from temperature distribution along the condenser zones. Described are the experimental setup, the test results, and the method used to derive the slug length from the available data.

Nomenclature

a	= groove width
b	= groove depth
D_v	= vapor core diameter
$FH1$	= forward heater at heat pipe 1
$FH2$	= forward heater at heat pipe 2
n	= number of grooves
NH_3	= ammonia
ΔP	= capillary pressure
TMM	= thermal mathematical model
σ	= surface tension

I. Introduction

IN the unique thermal control design for TV-SAT/TDF,[1] heat pipes are used "classically" on the north and south radiators for heat distribution, as well as for connections between the two radiators and vertically in the Earth/anti-Earth direction. In total, 88 heat pipes are utilized in the different configurations throughout the communications and the service module as shown in Fig. 1.

An essential aspect of the spacecraft thermal design is represented by the U-shaped heat pipes which act as thermal connections between high dissipating units on the Earth panels and the north and south payload radiators. Also, the unit seasonal temperature variations are minimized, since these units can reject their heat to either the north or the south radiator panel.

The design concept of the heat pipe network requires relatively high thermal conductivities where the heat pipes connect and cross. Hence thermally inactive sections in these areas have to be avoided. Inactive sections are mainly caused by portions of heat transport liquid not involved in the heat transport process and accumulated within condenser zones.

There are two phenomena which influence the amount of excess liquid: temperature dependent density variations within the working fluid (ammonia); and meniscus depression during operating conditions.

The latter contribution to excess liquid is based on the assumption that no meniscus depression exists over the entire groove length at zero heat transport. However, if a heat pipe is operating, a curved liquid-vapor interface is generated, which adjusts automatically so that capillary pumping is just adequate to meet flow requirements. As a result of the induced depression, a corresponding amount of excess liquid appears.

The amount of excess liquid can be decreased by reduced fluid inventory, however, at the expense of local dry-outs at the evaporator end and subsequent performance reduction.

Presented as Paper 85-1011 at the AIAA 20th Thermophysics Conference, Williamsburg, VA, June 19-21, 1985; revision received Jan. 4, 1986.

*Staff member.

II. Excess Liquid Formation

Three different hypotheses concerning the formation of excess liquid shall be proved in the following taking into account the heat pipe hydrodynamics characterized by evaporation, high velocity vapor flow, condensation, and liquid return by capillary forces.

Liquid Droplet Formation

Because of the high vapor flow, it is not possible that free floating liquid droplets will exist for a long time. Such droplets, if created during evaporation, will be carried away with the vapor and deposited in the condenser zone. This process, however, leads to the probability that a liquid film builds up there, which decreases to a large extent the heat transfer coefficient in this area.

Liquid Slug Formation

In a 0-*g* environment the excess liquid may accumulate at the condenser end of the pipe and form a plug which fills the entire cross section of the pipe. This so-called slug would reduce the active length of the heat pipe but would not affect the heat pipe operation of the remaining length.

Liquid Film Formation

A liquid layer on the condenser wall may be a stable configuration if the condenser is not located close to at least one end of the heat pipe. Owing to the low thermal conductivity of the liquid, the thermal performance of a heat pipe can be drastically reduced.

However, in combination with a slug, a liquid film is not a stable configuration, as shall be explained in the following. Consider a simple configuration with an evaporator zone at one end and a condenser at the other (Fig. 2a).

In case a slug has developed, a stable interface to the vapor core would be a half-sphere (although a shape somewhat different from this ideal contour will exist due to the influence of the flowing vapor). If the excess liquid forms a layer in the condenser zone adjacent to the slug, then two distinct and communicating liquid body formations would exist. The capillary pressure of the two surfaces are, however, completely different. For a half sphere liquid surface, the capillary pressure ΔP_s can be expressed by

$$\Delta P_s = \frac{4\sigma}{D_v} \tag{1}$$

with

σ = surface tension
D = vapor core diameter

and for the cylindrical layer by

$$\Delta P_f = \frac{2\sigma}{D_v} \tag{2}$$

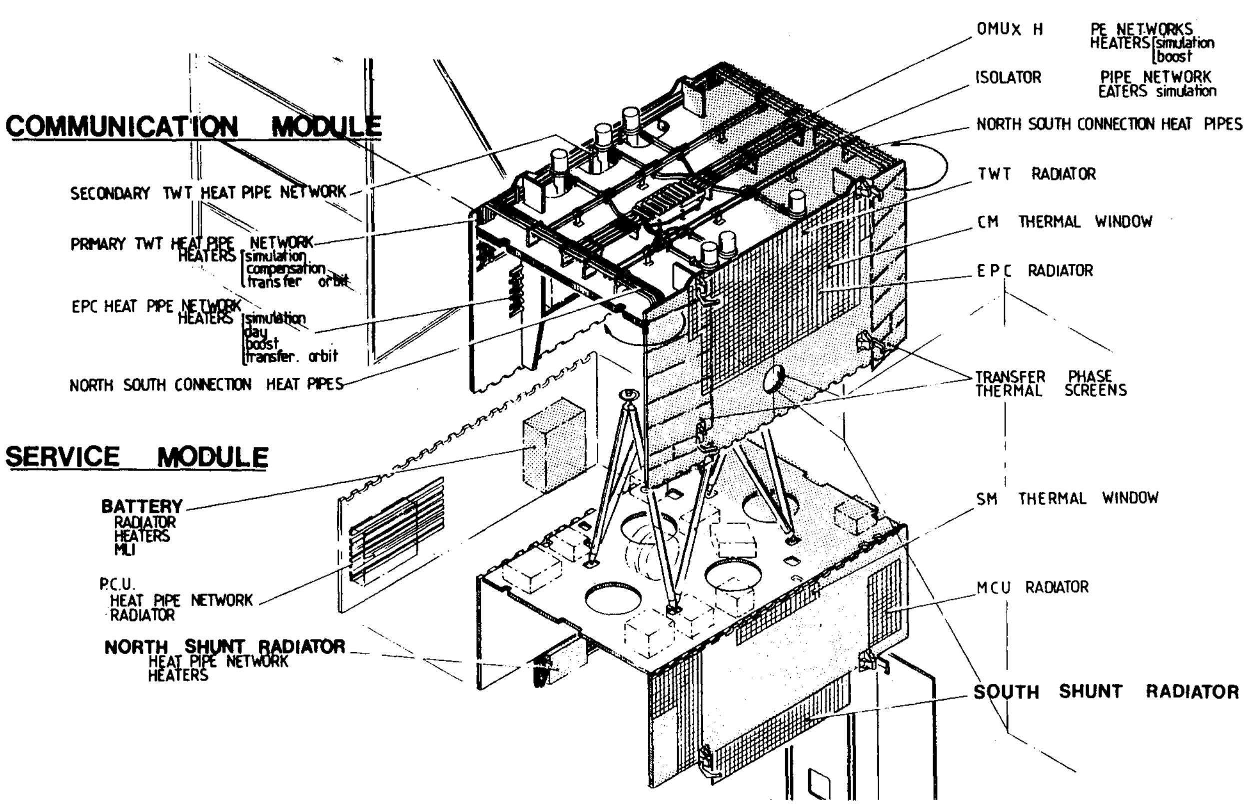

Fig. 1 Thermal control concept of the communication and service modules of TV-SAT/TDF.

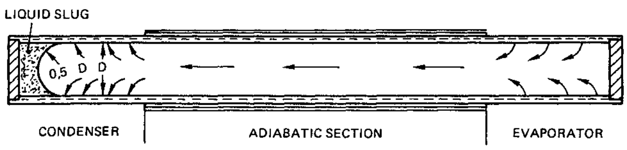

Fig. 2a Simple heat pipe configuration with liquid slug.

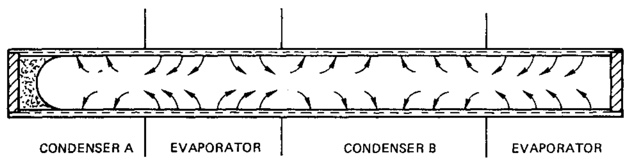

Fig. 2b Heat pipe configuration with different condenser/evaporator locations.

The capillary head of the slug formation is, therefore, twice as large as for the liquid layer. Consequently, the two formations cannot exist at the same time. Instead, the liquid of the layer formation will be drawn into the slug. Although the above relations are derived for ideal undisturbed liquid surfaces, the conclusion will basically be valid also for real surfaces. This is because the effective slug will always have two radii of curvature against one for the liquid film layer.

The described mechanism takes place even with small liquid overfill in the heat pipe. This happens because, in the beginning, excess liquid will accumulate in the corner between end cap and pipe wall, which, owing to its smaller meniscus radius, always provides a stronger capillarity than the liquid layer. It can therefore be concluded that a liquid layer in the condenser zone, which is located close to the pipe end, is not stable. This excess liquid will be drawn into the more stable slug configuration.

The above assumption is, of course, only valid if the two formations (film and slug) are placed in such a way that a liquid flow path exists between them. In Fig. 2b a typical situation is schematially shown, where the condenser is placed in the middle of the pipe, framed by two evaporator zones. The only liquid connection between this area and the slug area at the pipe end is via the grooves. However, since the capillary pressure head of these grooves in the evaporator zone is higher than that of the slug surface, a feeding of a possible layer into the slug cannot take place in this way. For this configuration it is necessary to consider qualitatively the condensation rates of the different areas.

For the configuration in Fig. 2b we can distinguish two distinct condenser areas: area A close to the pipe end and area B in between the evaporator zones. For area A the described mechanism applies, which means that excess liquid will be drawn into a slug formation. If we now assume that a liquid layer develops in area B, then the condensation rate drops rapidly due to the additional thermal resistance of the liquid. At the same time the condensation rate in area A increases and will be higher than the liquid amount which can be transported by the grooves to the evaporator zone. The excess liquid will consequently be drawn into the slug and this process continues until the nominal liquid amount for the liquid/vapor cycle has been established also in area B.

It can, therefore, be concluded that for a heat pipe with different condenser/evaporator locations a liquid layer formation is not stable, provided that a condenser area is located close to at least one end of the heat pipe.

III. Experimental Setup and Test Sequence

In order to prove the hypothesis that slug formation represents the more stable configuration in 0-g conditions, a particular heat pipe experiment was performed with two aluminum axially grooved heat pipes of parallel flanges used in the TV-SAT/TDF program. The heat pipe with the smallest diameter was used in order to achieve relatively long excess liquid length in the condenser zones. Both heat pipes had a length of 1258 mm with an evaporator length of 230 mm and a condenser length of 255 mm. ($D_v = 7$ mm; $a = 0.49$ mm; $b = 0.96$ mm; $n = 22$.) Figure 3 shows the whole test setup.

The two identical S-shaped heat pipes were filled with different ammonia fluid inventories as working fluid. HP1 was filled with 8.4 *g* NH_3. HP2 was filled with 10.0 *g* NH_3.

The fluid inventory of HP1 met the requirements for the TV-SAT/TDF heat pipes of maximum 25-mm inactive length within the whole operating temperature range, whereas the fluid inventory of HP2 was intentionally oversized for a better observation of the slug effect. The effect of condenser blockage by noncondensible gas (NCG) was negligible (2 mm at 30°C). This value was derived from test results obtained after 300 h wetting run at 85°C. The tests showed an NCG gas plug length of 60 mm at −58°C.

The predicted amounts of excess liquid formed as a slug in HP1 and HP2 are shown in Figs. 4 and 5, respectively. These plots reflect the contribution of excess liquid due to temperature variations within the working fluid as well as due to meniscus depression variations at different heat transport rates.

The temperature difference between the evaporator and adiabatic zone of about 1.7°C still does not indicate dry out conditions. This can be expected at a temperature difference of ≥5 °C.[3]

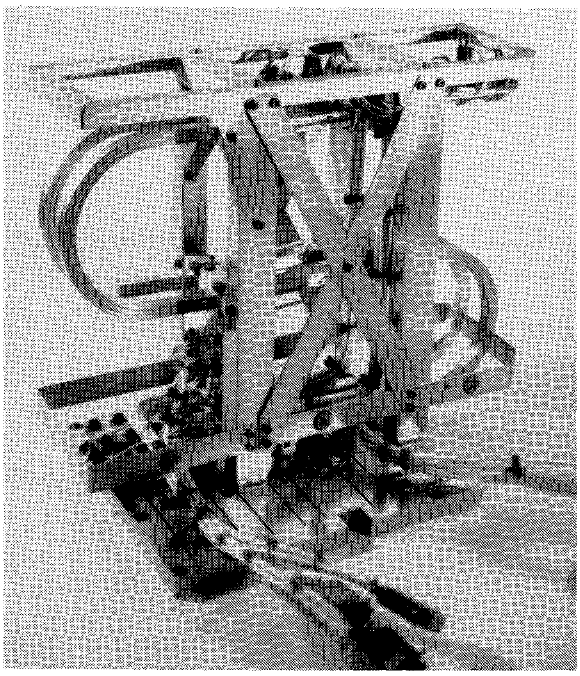

Fig. 3 Flight heat pipe experiment setup.

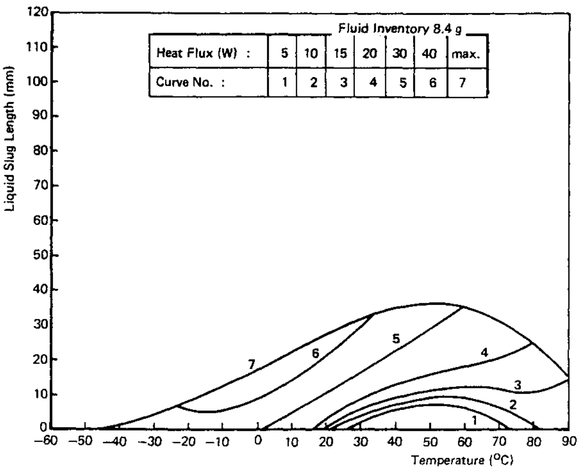

Fig. 4 Liquid slug length predictions for HP1.

Each heat pipe was equipped with a so-called forward heater (in the evaporator section) and a reverse heater (in the condenser section). The latter was installed to achieve a potential rejection of excess fluid from the condenser zone.

On each heat pipe, 9 temperature recording thermistors were attached, from which 6 were located in the condenser area, 2 in the adiabatic section, and 1 at the evaporator side end caps. Additionally, two thermistors were located on the mounting plate, which acted as heat sink. This base plate was furnished with slots perpendicular to the condenser zone in order to avoid leveling effects on the condenser zone temperature profile induced by that massive mounting plate.

The whole experiment was decoupled from the SPAS-carrier internal environment by a preshaped MLI blanket (10 layers single aluminized crinkled Kapton), which was mounted on a dedicated support structure. The total experiment duration was 37 h 45 min including switch-off periods. The power settings of the heaters within this period varied from 0 to 50 W for the forward heaters and 0 to 15 W for the reverse heaters in steps of 10 and 5 W, respectively.

IV. Flight Results and Data Reduction

The flight data obtained were temperature histories with the associated power status. A representative data selection is presented in Figs. 6 and 7.

In order to enable a decision to be made at which excess liquid formation type (slug, film or slug/film mixture) the temperature differences vs the condenser zone were produced, the following criteria were applied.

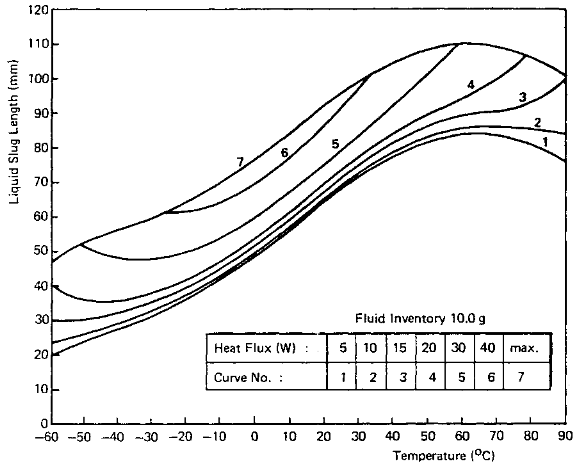

Fig. 5 Liquid slug length predictions for HP2.

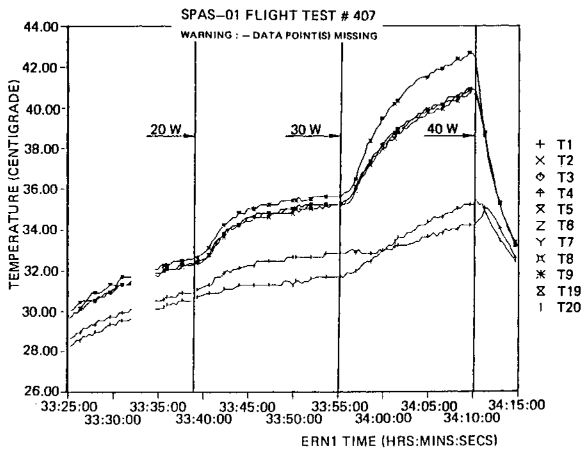

Fig. 6 Temperature history of HP1 (data selection).

In the case of a pure slug formation, an increasing temperature slope should be observed corresponding to the blocked condensing zone where vapor is not allowed to condense at the heat pipe wall in conjunction with a lower temperature difference between the base plate and the partially blocked condenser zone. At slug free condenser sections, the temperature difference between the heat pipe vapor and the profile wall should correspond to a condenser film coefficient of ≥ 1.3 W/cm^{2}K.

Assuming a liquid film formation, the temperature level would be constant over the entire condenser zone combined with a simultaneous high temperature difference between heat pipe vapor and condenser wall temperature. In the case where a combination of slug and film formation existed, a superposition of phenomena described should be observed.

Exclusively those data where the temperatures reached the best steady-state conditions for each power setting were selected for the test evaluation. For this condition Fig. 8 shows an example of the temperature distribution vs the heat pipe length. This is characteristic of all the residual evaluated temperature distributions with the slope at the heat pipe outer condenser end, nearly constant temperatures over the residual condenser and transport zone, and an increased temperature at the evaporator, corresponding to the installed power. This behavior indicates the correspondence with the first criterion of the slug formation hypothesis.

The second criterion for this hypothesis which refers to the condenser heat transfer coefficient was investigated by means of a 65 isothermal node TMM shown in Fig. 9 where the locations of the thermocouples are also identified. The thermal coupling between all nodes (except those which could be influenced by excess liquid) were determined by ground tests.

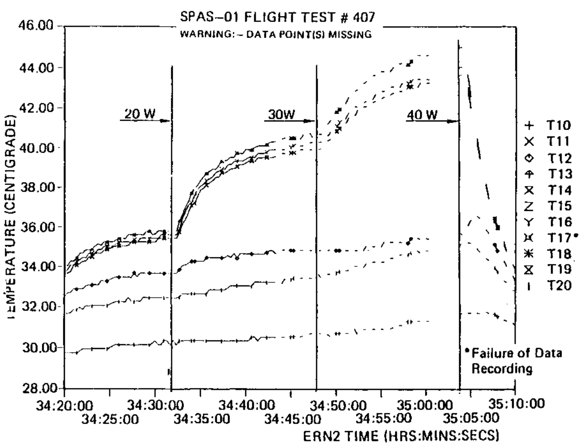

Fig. 7 Temperature history of HP2 (data selection).

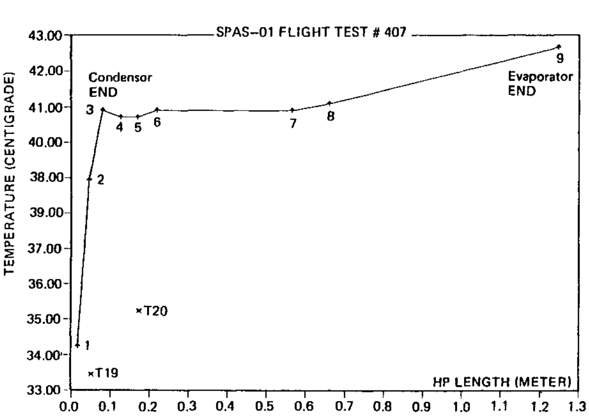

Fig. 8 Temperature distribution vs HP1 at 40 W FH 1 power.

Those couplings possibly influenced by excess liquid were adapted such that a best fit of the analytical and test temperatures were obtained with respect to the slope at the outer condenser end and the temperature level at the residual condenser zone at each power setting. As a result, the thermal coupling between heat pipe vapor and profile wall influencing the temperature level were found to be $3.4^{+2.6}_{-1.0}$ W/cm^{2}K. The relatively large uncertainty band of this value is established on the steep slope in the relationship of the film coefficients vs the specific heat resistance in the range of interest. This high value confirms that no liquid film existed in these zones because the radial heat transfer coefficient of this heat pipe is of the same

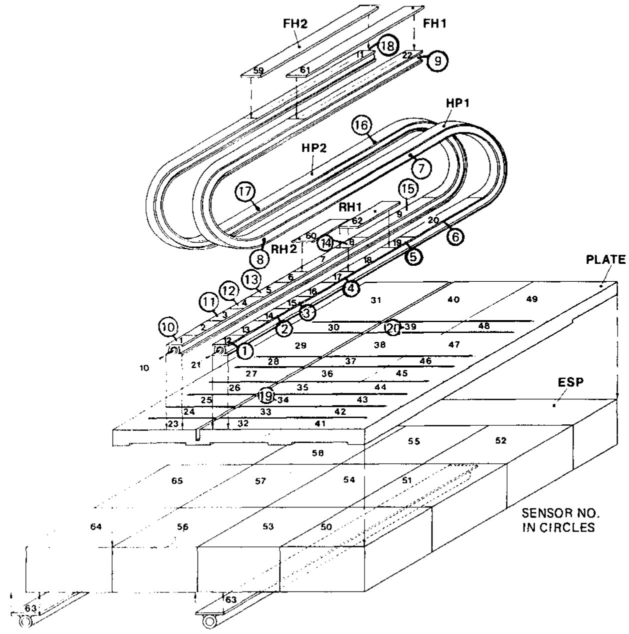

Fig. 9 TMM nodal breakdown with associated temperature sensors.

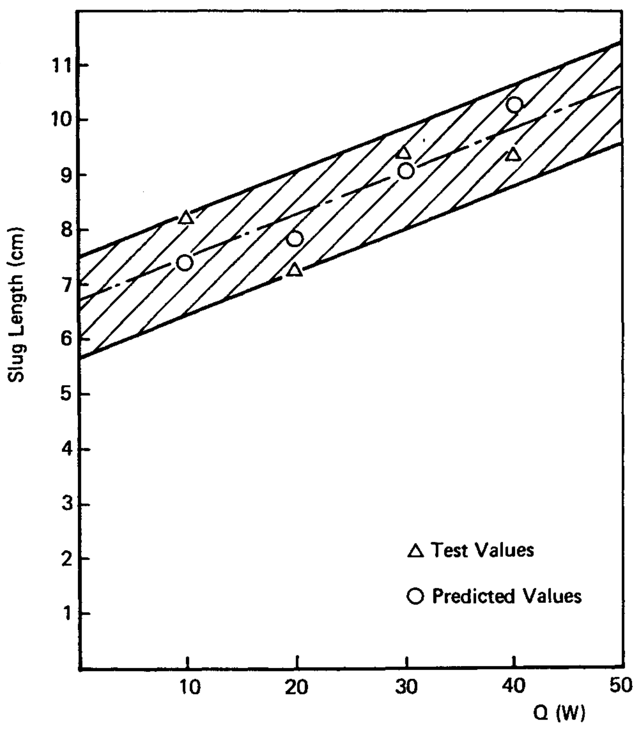

Fig. 10 Average slug length vs power at a temperature range between 33°C and 40°C.

order of magnitude. A rejection of excess liquid from the condenser zone by the operation of the reverse heaters was observed, however, a corresponding temperature increase within the condenser zone by the reverse heaters power settings.

V. Discussion of Results

The slug lengths calculated from the flight test results compared with the predictions showed the following results in dependence of the power setting: 3 to 6 cm for HP1, 8 to 10 cm for HP2.

The correlation with the predicted values was poor for HP1, with an aerage 2.3 cm lower predicted values. This less accurate correlation between flight test results and predictions may be influenced by several effects. One is that owing to the small slug length, any error in the data recording would result in relatively high effects. Additionally, the temperature slope at the condenser end may be caused by the pressure distribution in the vapor along the condensation zone. This assumption is supported by the fact that the same phenomena were observed during ground tests, where excess liquid could not be formed into a slug owing to the gravitational force. Contrary to expectations, the correspondence between the predicted and test values was good for HP2 with a mean deviation of about 10%.

In Fig. 10 the mean values for each power setting are plotted vs the predicted and the measured slug lengths. Because of the poor statistics the values irrespective of their temperature level were lumped together for each power setting. Therefore, a temperature dependence of slug lengths must be taken into consideration which is indicated by the shaded area. However, the power dependency of the slug length is deeply demonstrated, which can be appointed by a linear function. A comparison with the predicted calculations (light dots) showing the good correlation with the assumption of slug length development owing to meniscus depression.

VI. Conclusion

The evaluation of the experiment flight test results have clearly demonstrated that excess liquid in constant conductance heat pipes accumulates as slugs at condenser ends.

For the overfilled heat pipe, a good correlation between predicted and measured slug lengths was found which confirms the theory that the temperature (fluid volume expansion) and power (meniscus depression) dependency of excess liquid development.

This knowledge is significant for an evaluation of the TV-SAT/TDF-1 heat pipe design which is based on the assumption that no film formation of excess liquid will degrade thermal conductivities between heat pipes and connected equipment.

It can be summarized that the TV-SAT/TDF heat pipe fluid inventory has been properly chosen to provide the required heat transport capability even considering low excess liquid occurrences.

Acknowledgment

This paper is based on work performed in the frame of the TV-SAT/TDF-1 contract awarded by CNES, TDF (France), DFVLR and Bundespost (Germany) to the contractor EUROSATELLITE. The authors acknowledge the valuable discussions with various specialists within these organizations and within the Thermal Control Department of MBB/ERNO which supported the preparation of the paper.

References

[1]Giovagnoli, F., "An Advanced Thermal Control for the French-German Direct to Home Broadcasting Satellites TDF1/TV-SAT," *International Astronautical Congress,* JAF 82.328.

[2]Meyer, R. and Laux, U., "Design Aspects of TV-SAT/TDF1 Heat Pipes," ESA-SP-200, *International Symposium on the Environment, and Thermal Control Systems for Space Vehicles,* Toulouse, Oct. 1983.

[3]"Heat Pipe Qualification Requirements," *ESA PSS* Vol. 49 (TST-01), March 1983.