# AIR EVOLUTION IN FUEL FLOW UNDER DECREASED PRESSURE CONDITIONS: EXPERIMENTAL STUDIES AND ENGINEERING CODE DEVELOPMENT

**E.E. Kitanina *, D.A. Bondarenko **, D. Morrison *****
*** Saint-Petersburg State Polytechnical University, ** EADS RTO Sk LLC,**
***** Airbus Operations Ltd**

## Abstract

*The main purpose of the work presented in the paper was to develop dedicated software for the calculation of gravity fuel flow in a complex pipeline system with various hydraulic resistances. For that purpose air evolution in kerosene under the effect of gravity flow with various hydraulic resistances in the pipeline was studied experimentally. The study was conducted at pressure ranging from 0.2 to 1.0 bar and temperature varying between -20°C and +20°C. The complete set of empirical correlations obtained by experimental analysis was implemented in the engineering code. The calculation results were verified against both steady and unsteady experimental data. The comparisons lead to the general conclusion that the software provides fast and fairly accurate calculations of the fuel flow rate under air evolution conditions.*

## 1 Introduction

Air evolution in kerosene flow may cause issues in aircraft fuel systems. Initially fuel is saturated by air at pressures and temperatures corresponding to ground surface conditions. The fuel supplied to the aircraft during fueling is usually saturated with air under atmospheric pressure and ground temperature conditions. In cruise flight the ambient pressure drops, leading to the fuel oversaturation with air. Moreover the over-saturation of the fuel with air is large due to the temperature decrease up to -30ºC. In the case of pump deselection, pressure in the pipeline with pure gravity flow is contingent on the ambient pressure and fuel level in the tank only. Air can evolve from fuel, resulting in a flow rate decrease.

The air flow rate decline can be due to both the flow conditions (pressure, temperature) and the pipeline design. Substantial air evolution may occur as oversaturated fuel passes through the flow limiter (diaphragm) or other local resistance. Experience shows that pressure has a limiting value: above the limit air evolution is virtually imperceptible, whereas below the limit oversaturation drops sharply to provoke intensive air evolution and, consequently, a decline in the fuel flow rate.

The gas phase effect on pressure losses related to friction and the pressure leveling component can be quite reliably handled within the Chisholm model [1] based on the Lockhart and Martinelli approach [2]. The much less studied issues are the calculation of the pressure losses at the local resistances under air release conditions and establishing the gas fraction in the flow downstream of the local resistances [3]. There is a definite lack of scientific evidence that would allow researchers to describe the two-phase flow through the diaphragm under air evolution conditions. Moreover the transition from foamy to stratified flow can occur in a tilted pipeline segment. However the standard calculation methods mentioned above are devised for the foamy flow mode and do not allow the transition point coordinate determination.

Parametric calculations are required to establish the flow rate in aviation fuel systems under different operating conditions. Numerical simulation of two-phase flow in such systems still remains an intractable task. As an alternative to this approach, we developed a flow simulation tool that can take into account the experimental data on air evolution in pipeline elements and on the effect of this process on pressure losses due to friction and flow acceleration in individual pipeline segments.

## 2 Experimental research

### 2.1 Experimental technique and methods

More than 200 experiments were performed to study the dissolved air evolution process and pressure losses in individual pipeline elements. The experiments were conducted using TS-1 jet fuel in several test pipelines.

Though different pipeline segments were used depending on the research task, the main features of the test rig design remained identical. The test rig included two fuel tanks and a pipeline working section with valves on both ends. Each tank had a volume of 3 $m^3$. In all the cases the test rig was prepared for the test following the same steps. First, fuel in the upper tank was saturated with air by sparging at atmospheric pressure and the specified temperature and air was evacuated from the entire system to reach the given pressure. As a result, the fuel in the upper tank got oversaturated with air. Finally, the valve was opened to let the fuel flow into the experimental pipeline. The test rig control as well as data saving and pre-processing were provided by a specifically designed automatic system. Fuel temperature and pressure along the pipeline working section and fuel flow rates and pressures at the pipeline inlet were obtained for every experiment.

The research was conducted in the pressure and temperature ranges of 0.2–1.0 bar and -20 to +20°C, respectively. Temperature was measured by a resistance thermometer. The measurement error did not exceed one degree. Pressure was measured by standard Metran pressure sensors with a variable range. The pressure measurements error was 1% of the measured value. No air evolved at the pipeline inlet in any of the test cases. The fuel velocity in this section was defined based on the supply tank fuel level measured by calibrating the level meter. The velocity at the pipeline inlet varied between 0.4 m/s and 1.5 m/s. The velocity error was estimated at 5%.

A specific technique based on dissolved air concentration (C [kg/kg]) measurement was applied for air evolution calculation. The concentration measurements were taken within the range of $5 \cdot 10^{-5} \div 2.5 \cdot 10^{-5}$ kg/kg. The main idea of the method is illustrated by the following example. Let the dissolved air concentration be measured at the pipeline inlet, $C_0$, and in (i) section, $C_i$. Then the mass flow quality of evolved air can be calculated as follows: $X_i = C_0 - C_i$. To the best of our knowledge, this gas content evaluation technique has never been used before. In our experiments the dissolved air concentration was measured by chromatographs. A fuel sample was supplied to chromatographs by a specifically designed sampling system. The method used for measuring the evolved air content in the jet fuel flow is discussed in detail in [4]. The dissolved air concentration error was about ±20%. Note that the majority of experiments were carried out at rather low pressure values. This explains why the volume flow quality occasionally exceeded 50%, although the corresponding mass flow quality value was rather low.

The tank fuel level, pressure and temperature were measured once per second. A statistical data manipulation method and a bad results rejection filter were applied. Then the results were averaged over a minute and over the total experiment time. The velocity value was calculated using the fuel level change during a minute. The dissolved air concentration measurements required much more time because of the time-consuming fuel sample collection process. Usually an experiment was completed in 18-20 minutes, with about 3-5 fuel samples collected, transferred to the chromatograph and tested. During this time interval the fuel level in the supply tank changed by 0.1–0.15 m and pressure decreased by a little more than 1 kPa, i.e. by 5%. The relatively small pressure change allowed the flow regime to be described as stationary. In the case of unsteady flow regime the pressure could not be averaged. Only one measurement corresponded to the pressure value. Therefore the pressure error increased to 20%.

In addition to taking instrumental measurements, in some experiments we observed the two-phase flow modes through the clear pipeline segments.

## 2.2 Working pipeline designs

The experiments were conducted in several test pipelines.

Initially, the fuel flow was studied in an unbranched pipeline [5]. The corresponding test rig is illustrated in Fig. 1. The ∅ 0.015 m experimental pipeline included vertical ($L_1$ = 1 m) and horizontal ($L_2$= 0.5 m) segments connected by a smooth bend with a radius of 0.15 m. The inlet part of the pipeline could be tilted by different angles. The maximum tilt angle was 90º. The outlet part was always horizontal. A diaphragm was installed in the upper part of the working pipeline section. Two diaphragms with holes of different diameters, 7.5 mm and 10 mm, were used. Temperature, pressure and dissolved air concentration were measured at the sections a-d located after the diaphragm. (See Fig. 1).

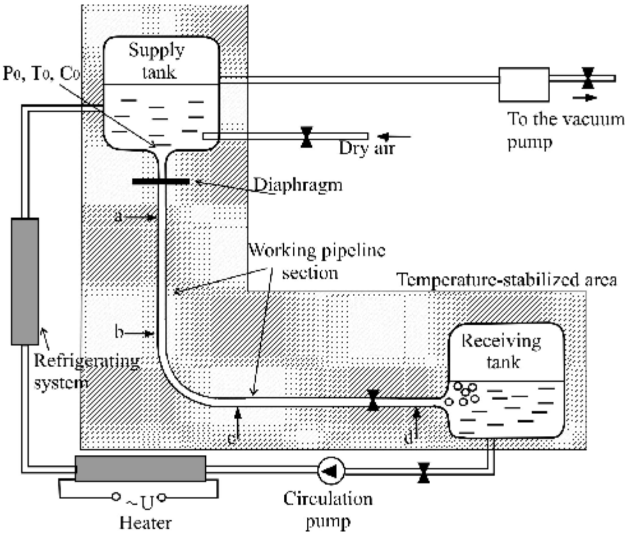



Fig. 1. Test pipeline for the study of the diaphragm's effects. Side view.

The second test rig (see Fig. 2) was built specifically for the study of air release at local resistances and assessment of its effect on their resistance value, therefore measurement of the flow mass quality downstream of each resistance appeared as a top priority and a big challenge in the testing. A diaphragm installed 0.5 m downstream of the inlet diffuser was followed by a clear section of the same inner diameter (38mm), a set of local resistances, including a ball valve, a 117 mm long Ø 38 mm to 76 mm pipe expansion, a smooth $90^0$ bend with a 300 mm bend radius, a long straight segment (over 2 m) and another $90^0$ bend. The straight segment following the second bend included a 117 mm long Ø 76 mm to Ø 38 mm contraction, an outlet with a ball valve and a connection to the receiving tank via a flexible cable.

Specific tests were performed to study the effect of the tilted segment on the two-phase flow rate. For this purpose a pipeline segment located between the expansion and the second $90^0$ bend (between point e and f) was tilted by 10 and 20 degrees.

The pipelines had clear sections for viewing and recording the two-phase flow behaviour downstream of the local resistances (grey coloured rectangles in Fig.2).

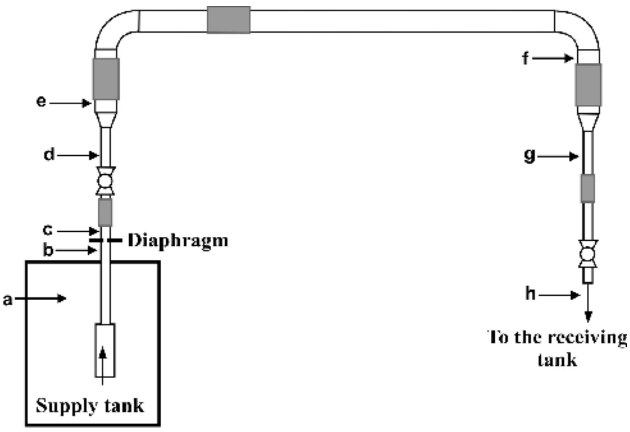



Fig. 2. Test pipeline with various local loss segments (view from above). a, b, c, d, f, g and h – pressure measurement and fuel samplings points

In further experiments, we built a branched pipeline (see Fig.3). As is evident from the figure, the working pipe section contains two diaphragms, expansions, contractions and bends. The pipeline has branchings at the upper tank outlet and the lower tank inlet. Two of these branches run into a single pipeline of the same diameter at a $30^0$ angle. The flow from the third branch after the $90^0$ degree smooth bend runs into the Ø 76 mm pipeline. Pressure, temperature and mass flow quality were measured at the sections a-f. In addition, differential pressure sensors were placed along the pipeline.

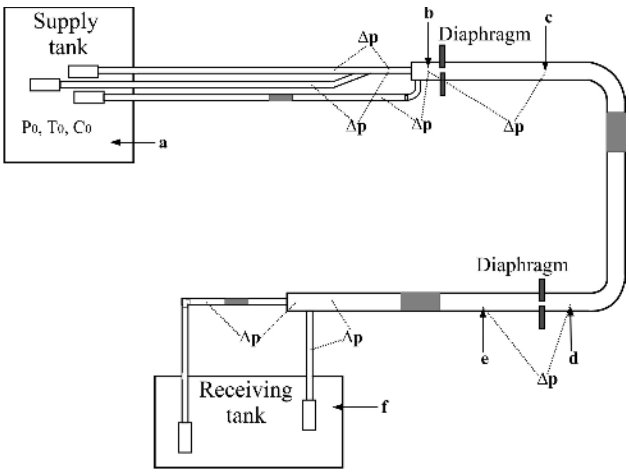



Fig. 3. Branched pipeline simulating the refuelling system (view from above).

Our empirical equations and calculation results were further verified against the independent experimental results provided by Airbus. Fig. 4 presents a scheme of the test rig build by Airbus team. The test rig has nearly the same geometry as a real pipeline used in aircraft fuel systems. It represents the left wing and centre tank refuel sub-system.

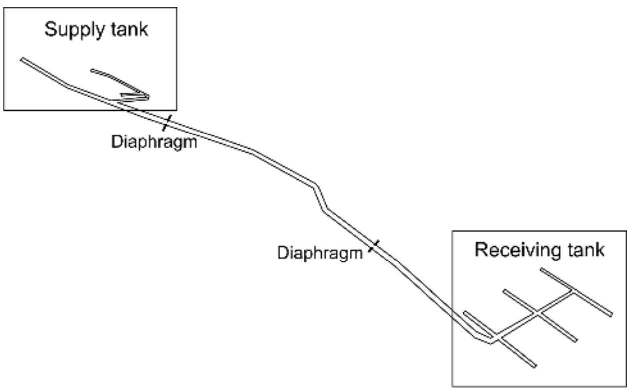



Fig. 4. Airbus test rig. Side view.

The experimental data were obtained for TS1 and JetA-1 fuel flow in the pipeline with $5^0$ and $39^0$ tilted segments. Airbus's tests addressed gravity flow in the pipeline comprising two diaphragms, expansions, contractions, bends and two tilted segments. The tests were carried out over the temperature range of -20°C to +50°C. The working pressure range corresponded to the flying altitudes of 0 (ground level) to 43 Kft. In Airbus's tests, the fuel flow rate was found from the data on time steps and fuel levels in the tank. In these experiments pressure and mass flow quality along the pipeline were not measured.

## 2.3 Key experimental outcomes

Our measurements indicated that air evolution in oversaturated fuel starts as pressure drops abruptly to a certain boundary value. It was shown that this boundary pressure value can be calculated as a sum of the pressure limit value and the terms depending on temperature and fuel velocity. The method elaborated for boundary pressure evaluation is discussed in detail in [5]. It was shown that the corresponding equations can be used for the pipelines comprising different pressure loss segments.

The influence of the pressure drop on air evolution can be clearly seen in Fig. 5 and 6. The photos show the flow pattern downstream of the diaphragm under different external pressure conditions. In Fig.5 the amount of evolved air is negligible. The flow in the pipeline is one-phase.

Fig.5 Fuel flow downstream of the diaphragm. $P_0$= 60 kPa, $T_0$ = 293K, $U_0$ =0.65m/s. Virtually no air released.

The results obtained at a lower pressure level are quite different. It can be concluded that air bubbles start forming in much larger quantities at pressure under 60kPa (Fig. 6), although the phases have the same velocities after the diaphragm.

Fig.6. Fuel flow downstream of the diaphragm.
$P_0$= 20 kPa, $T_0$ = 293K, $U_0$ =0.65m/s. Intensive air evolution.

In our experiments we notice that the diaphragm usually provokes the most intensive air evolution in fuel flow. A large set of experimental data was analyzed to produce empirical correlations for the pressure drop and air evolution after the diaphragm [6]. It was discovered that the diaphragm pressure loss coefficient depends on the volume flow quality downstream of the diaphragm. The obtained correlations provide adequate results in a wide range of diaphragm to pipeline diameter ratios. Note that almost no air evolves downstream of the segments generating a minor pressure drop, e.g. the bends, contractions, expansions and branching. However these elements can have a strong impact on two-phase flow modes. It was demonstrated that the effect of the pipeline branching on the two-phase flow behaviour can be taken into account by using the one-phase flow correlations [7]. Some experimental results and their generalizations are presented in our papers [5, 6]. All the correlations obtained were used in the new gravity flow simulation software tool.

Empirical equations were derived from our experimental data to calculate pressure losses in the tilted pipeline segment at very low mass flow quality and fairly high volume flow quality. Conventional methods prove inefficient [8] under the conditions at hand due to co-existence of two flow modes in different parts of the titled segment. In many experiments we observed stratified flow in the upper part and foamy (bubble) flow in the lower part of the tilted segment. The flow mode change is shown schematically in Fig. 7.

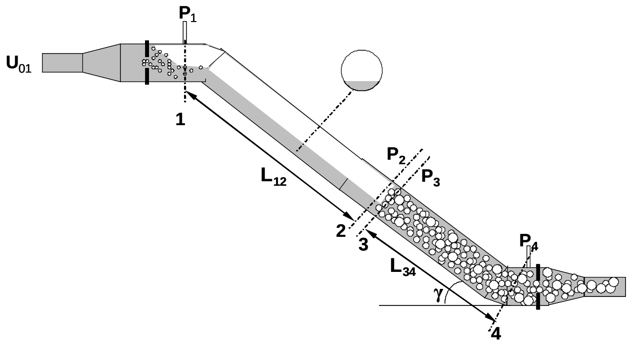



Fig. 7. Flow modes in the tilted segment.

The stratified and bubble flows observed in our experiments near the transition cross-section are shown in Fig. 8 and 9, respectively.

Fig.8. Two-phase flow in the tilted segment.
P=20 kPa, T =273 K, $U_0$ =0.71 m/s, tilt angle 20 degrees.

Though it is easy enough to calculate the pressure in each individual part, the flow mode transition point proves to be a priori unknown. The method of calculating the two-phase flow pressure in a titled pipeline segment is presented and substantiated in [8]. We built a complete calculation chain including pressure drop equations for both flow modes, an equation taking into account the change in kinetic energy during transition and an empirical equation for calculating the pressure drop in the tilted pipeline segment. This helped estimate the stratified to foamy flow transition point coordinate.

Fig.9 Two-phase flow after the tilted segment and the bend before the contraction. P = 20kPa, T =273 K, $U_0$ = 0.64 m/s, tilt angle 20 degrees.

## 3 Engineering software

### 3.1 Calculation algorithm: distinctive features

#### *3.1.1 Unbranched pipeline simulation*

The software's calculation algorithm is based on the following fuel flow velocity correlation:

$$U_0 \propto \sqrt{\frac{p_{inl} - p_{out}}{\sum_{n=1}^{k}\lambda_{n,fric}\frac{\rho_n l_n}{2d_n} + \sum_{i=1}^{m}\zeta_{loc,i}\frac{\rho_i}{2} + \sum_{n=1}^{k}(\Delta p_{ac,n} + \Delta p_{z,n})/U_0^2}}$$

As indicated by the equation, the fuel velocity ($U_0$) is found through the calculation of pressure losses in all the pipeline segments. The iteration cycle is required to take into account the mutual effects of the fuel velocity, amount of evolved air, friction and local loss coefficients. Thus starting from some zero approximation, the cycle determines the velocity that provides a balance between the levelling pressure and pressure losses caused by friction and local resistances. Importantly, the evolved air concentration level has a strong impact on pressure losses in the case of two-phase flow.

#### *3.1.2 Branched pipeline simulation*

In the gravity flow conditions, where the fuel flow rate is a definable quantity, the pipeline branching leads to a substantial increase in the number of new calculation procedures and iteration cycles.

The algorithm for the calculation of the gravity flow in a branched pipeline performs several steps. As the first step, it calculates the flow parameters along the main pipeline ignoring the branches. The solution is used as the initial approximation in further calculations. As the second step, the algorithm runs a recursive procedure to search for the branches and calculate the flow parameters in the lateral branches. The pipeline tree is searched through as follows. The algorithm identifies the pipeline segment that the total fuel flow passes through when travelling from the upper tanks to the lower tanks. This segment is referred to as the total flow segment. The branch search and calculation starts from the total flow segment. First the algorithm searches for the upstream branches. The fuel flow rate and other flow parameters in the pipeline branches are calculated based on the general mass and motion quantity balance equations. As the initial approximation, the algorithm uses the flow rate upstream of the branching related to the number of branches in the given joint segment and pipeline diameter in each branch. After the current branch calculation has been completed, the search continues in other upstream branches. As the next step, the search is performed in similar manner and the flow parameters are calculated in the pipeline branches located downstream of the total flow segment. After the calculation has been completed for the branch, adjustments are made in the solution for the flow upstream of the branch.

As stated above, the total flow rate in gravity pipelines is calculated through an iteration process (i.e. global iterations). Each global iteration comprises branch search procedures and additional internal cycles for the calculation of the flow splitting in the branches. After all the internal cycles are completed, adjustments are made in the global cycle solution with due regard for the altered pressure losses in the segments downstream of the branches.

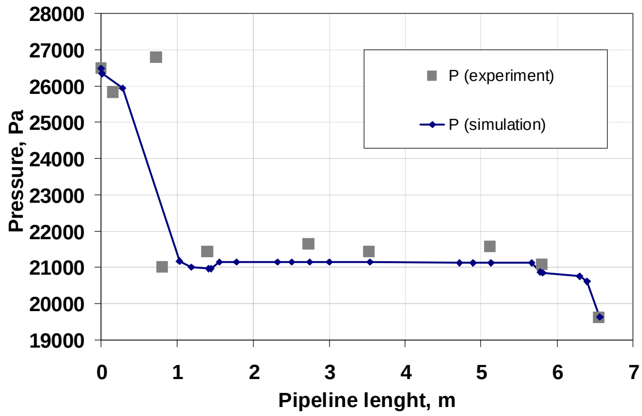
The software implementing the above algorithm is designed in C# language in Microsoft Visual Studio environment and has an extensive user-friendly interface. With this software tool, the user can build a 3D model of the pipeline and all the local resistances, specify the fuel type (JetA-1, TS-1), temperature, pressure or time variations of the ambient pressure and temperature, and calculate the unsteady-state fuel flow rate or its time variations, and the gas content and its values versus pipeline length and time.

## 3.2 COMPARISON OF THE SIMULATION AND EXPERIMENT

### *3.2.1 Flow after a diaphragm*

Our experiments on different test rigs (see section 2.2) always demonstrated a significant influence of the diaphragm on the flow parameters in the entire pipeline. The point is that in most cases a pressure drop after the diaphragm provokes intensive air evolution. The two-phase flow modes downstream of the diaphragm can lead to considerable changes in fuel flow rate in a pipeline. The empirical correlation obtained by generalization of the first test rig experiments was implemented in the software and thoroughly verified by subsequent results.

Fig. 10 gives a verification example showing the distributions of pressure and evolved air mass flow quality along the pipeline. The data were obtained at P = 20 kPa and T =255 K on the second test rig (see Fig. 2). The calculation results (blue dots and graphs) are compared with the experimental data (grey dots). The charts reveal tendencies typical for the entire experimental series. A dramatic pressure drop is clearly seen after the diaphragm (Fig. 10, above). This corresponds to an increase in the amount of the evolved air (Fig. 10, below). As can be seen from the figure, the other local loss segments located downstream of the diaphragm have much weaker influence on the flow parameters as compared to the diaphragm. The pressure drop after the diaphragm is calculated with a very good accuracy ($\delta P<1\%$). Moreover, we notice good agreement between the experimental and calculated mass flow quality data, except for the value before the diaphragm. However this mass flow quality value is close to the experimental error.



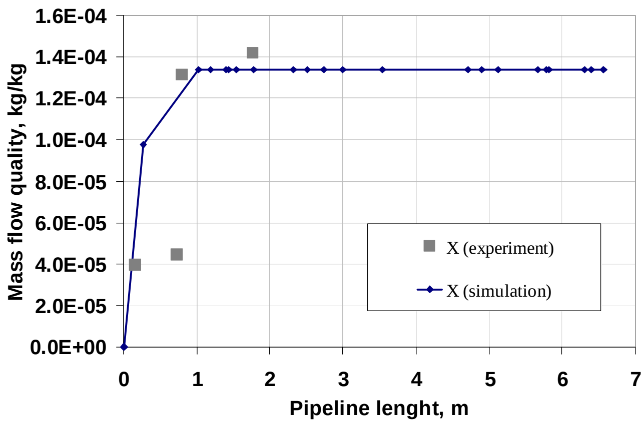




Fig. 10. Distribution of pressure (above) and mass flow quality (below) along the pipeline. Correlation with experimental data.

The comparison covers the entire operating parameter range: pressure $p_1 \cong 0.2$–1.0 bar; temperature -20 °C, 0 °C, +20 °C; fuel velocity at the pipeline exit -0.56 m/s to 1.28 m/s. Generally, we observe strong consistency between the calculated and experimental results for the pressure value downstream of the diaphragm in all the two-phase flow experiments (uncertainty less than 8%). The calculated and experimental fuel velocity values display a good match too over the entire parameter range, with a relative error not exceeding 10%. The flow quality is calculated with uncertainty of 10-35%. The uncertainties can stem from both the calculation model constraints and experimental errors.

### *3.2.2 Flow in a branched pipeline with two diaphragms*

This paragraph features the flow simulation results obtained for the pipeline shown in Fig. 3. In this case two diaphragms were installed in the working pipeline section. Thus the experimental data allowed verifying the empirical equations obtained earlier for a single diaphragm and other local loss segments. The algorithm developed for the branched pipeline was tested by comparing the fuel flow rates in the branches. The peculiarities and accuracy of calculations performed for horizontal and tilted working pipe sections are considered separately.

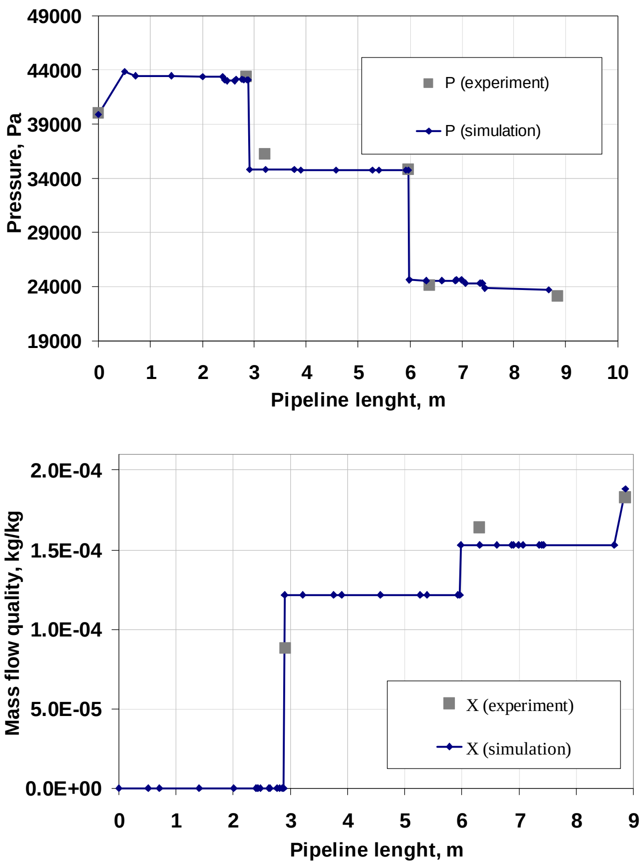



Fig.11. Distribution of pressure (above) and mass flow quality of evolved air (below) along the main branch of the horizontal pipeline.

Fig. 11 offers an example of pressure and mass flow quality distributions along the main branch of the horizontal pipeline, with a comparison of the simulated and experimental results. Clearly visible in the graphs are the sharp pressure drops in the sections downstream of the diaphragms. From the results obtained it may be concluded that the diaphragms have the strongest impact on the flow behaviour in the horizontal pipeline in this series of experiments, despite multiple local resistances and pipeline branches and confluences. It is significant that the experiments and calculations provide evidence of intensive air evolution in the segment immediately following the diaphragms.

Generally, comparisons display a fairly good match between the simulated and experimental flow parameters in the complex branched pipeline with intensive air evolution. The parameter of primary interest, the gravity flow velocity, is calculated with a mean error of less than 8%. We believe that the calculation error in this series of experiments stems mainly from mutual influences of the local resistances.

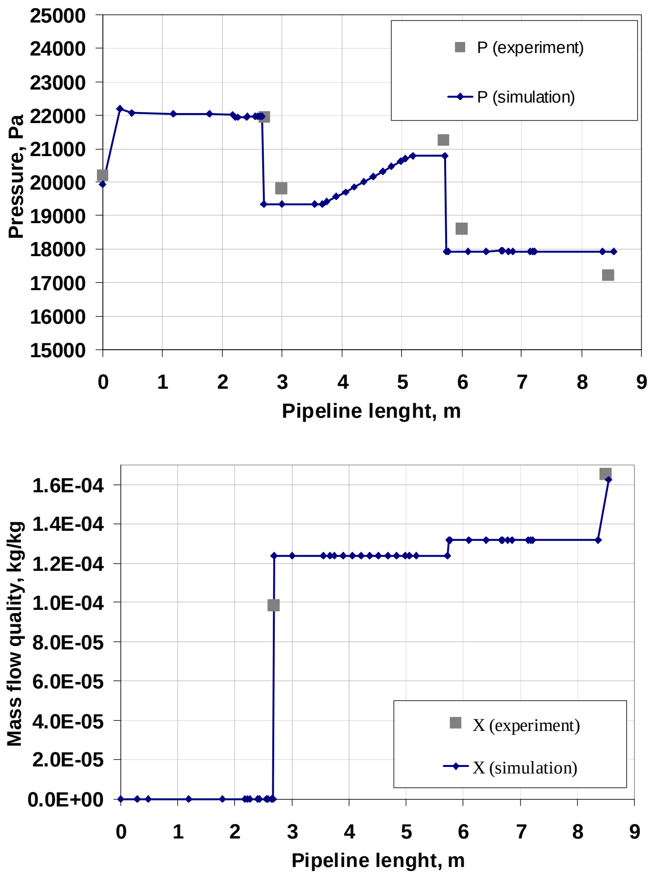



Fig.12. Distribution of pressure (above) and mass flow quality of evolved air (below) along the main branch of the tilted pipeline.

The next series of experiments was performed in the tilted pipeline. According to the empirical calculation model, the two-phase flow regime changes in the tilted segment. Under certain conditions, laminated flow forms in the upper part and foamy flow in the lower part of the tilted segment. This results in a specific pressure distribution pattern and undoubtedly affects the flow velocity. The flow transition coordinate was calculated by the empirical formulas [8].

Fig. 12 illustrates the pressure and mass flow quality distribution along the main branch of the tilted pipeline. Like in the previous case, an abrupt pressure drop is observed downstream of the diaphragms, with the biggest discrepancy between the simulated and experimental data registered downstream of the first diaphragm, caused by the abrupt expansion and confluence of several upstream branches. The two-phase flow regime changes between the first and second diaphragms, with the pressure remaining constant in the laminated flow segment and growing higher in the rest of the tilted segment where the foamy flow develops.

The comparison of the calculated and experimental data for the tilted pipeline reveals a 4 to 23% error in the mean fuel flow velocity calculation. The error is largely due to the inaccuracy in calculating the flow transition coordinate, which proved to be quite a challenge for the test pipeline in question.

The calculated fuel velocities in the branches were compared to the experimental data for all the test cases. In general, the comparison produced a good result, with the average flow velocity calculation error for all the inlet branches not exceeding 16% in most cases, and a higher discrepancy observed for the velocity in the inlet branches (up to 25%) in some cases. Most often higher errors occurred in the tilted pipeline experiments. It is evident that the uncertainties in the simulation of the two-phase flow mode transition in a tilted pipeline can result in inaccurate fuel flow rate values both for the entire pipeline and in its individual branches. On the other hand, these experiments revealed high flow pulsations that affected the measurement accuracy of the flow meters installed in the branches.

### *3.2.3 Airbus unsteady-state experiments*

The software was further verified by comparing its outputs to independent experimental results. As was mentioned in Chapter 2.2, Airbus's research focused on JetA-1 gravity flow at low pressure in a pipeline of complex geometry (See Fig. 4). The fuel flow rate was defined as the time derivative of the fuel level in the tank.

The calculations were complicated by the pipeline having two inclined segments, the first tilted by 5 degrees and bounded by two diaphragms and the second tilted by 39 degrees and immediately following the first and ending with a horizontal segment before the branching. A change from stratified flow to foamy flow in both segments was clearly observed though transparent pipes. It is notable that our empirical method allowing calculations of pressure drop in a tilted segment was designed for a single segment located between two diaphragms. However the simulation results show that this method can be applied to more complicated pipelines including two tilted segments.

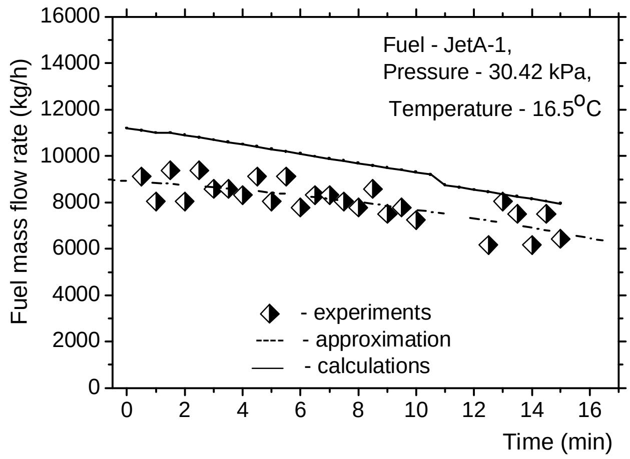



Fig. 13. Fuel flow rate versus time.
Simulation and Airbus test results.

The comparison of the experimental points and the function approximating these data (dashed line) along with the calculated curve are presented in Fig. 13. The review of the results leads to the following conclusions: a) the fuel rate was measured with a high error in the tests; b) the calculated and experimental curves differ by about 25% at the beginning and by 20% at the end of the process. Besides, it is quite probable that the simulation model does not fully account for the pressure losses in the two-phase flow through the complex pipeline with multiple local resistances and two tilted segments. The uncertainty may result from the mutual influences of local resistances and unsteady phenomena produced by the flow regime transition in some experiments.

## 5 Conclusions

The paper summarizes the main results of research into air evolution in fuel. Several experimental rigs were built to study the the effects of different local loss segments on the gravity fuel flow. The article describes the structure of the two-phase gravity flow software tool. Its simulation model is based upon the empirical equations. The simulation results are compared to the experimental studies of steady- and unsteady-state flow in different pipelines of complex geometry. The software tool provides fast and fairly accurate calculations of the fuel flow rate in the fuel system under air evolution conditions.

The study was performed in collaboration with Prof. E.L. Kitanin, experimental team leader Dr. O.A. Merkulov, Dr. V.L. Zherebzov, Dr. M.M. Peganova, Dr. S.G. Stepanov, computational team leader Dr. P.A. Kravtsov, Eng. V.L. Rappoport, Eng. M.V. Poltavtsev who deserve a mention as co-authors.

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## Symbols

p – pressure;
Δp – pressure change;
T - temperature:
U - fuel velocity
C - mass concentration;
X – mass flow rate;
l – length;
d – diameter;
ρ – density;
λ – one-phase friction coefficient;
ζ– local loss coefficient;

## Indexes

in - inlet;
out – outlet;
acc – acceleration;
z – leveling;
0 – supply tank parameters;

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