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Liquid Penetrant Testing: Industrial Process

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Abstract

Non-destructive inspection is an area of great interest and importance for the aviation industry. These kind of controls are routinely applied in various phases of design, development and production of manufactured. The present paper describes the whole process of inspection with liquid penetrant and the methodology adopted by Alenia for quality control of this process. Among the various methods of non-destructive testing, liquid penetrant is mainly applicable to metallic materials and detects discontinuities of size greater than 0.01 mm, provided that they are open on the surface. Due to broad typology of defects found and materials tested by this method, it is difficult to define an unique class of optimal parameters that describe the process. In this work we report an analysis of the different diagnostic target, according to the process parameters. Finally, we discuss the modeling activities developed within the last years.

Keywords: `Liquid penetrant testing, industrial process, mathematical modeling.`

1. Introduction

Non-Destructive Inspections (NDI in short) have been and are still an area of great interest and importance for aviation industry. They are routinely applied in several phases of design, development and implementation of aeronautic structures. This paper describes non destructive inspection activities at Alenia Aeronautics, explaining the characteristics and peculiarities of each inspection method. Particular attention is given to the "Penetrant Testing" (PT) method used for inspection of metal and non-porous material in order to detect superficial discontinuities. The whole process is described, detailing all its complex stages, defining the parameters, and the physical laws that regulate the process.

Because of the complexity of the phases of liquid penetrant inspection process, where several parameters interact, we want to point out the need to have a mathematical model based both on practical considerations (derived from observation of the intrinsic structure of materials used for inspection) and on technical considerations (according to the physical law that control the penetration of a liquid in a capillary). Such a model could be used in order to simulating the process, making predictions and optimizations on the set up values to use, and increasing the sensitivity of this technique in the detection of defects in critical circumstances.

2. Alenia Aeronautics

Alenia Aeronautics is a company of the Finmeccanica society. This company is one of the major European players in aerospace, it works with full integration capability through design, manufacture, and support of advanced military and commercial aircraft. Alenia is among the world leaders in aerostructures, "best in class" in technologies and in the industrial process of composite material, leader in the overhaul, maintenance, and modification of military and civil aircraft. It keeps up and develops collaborations with the most outstanding aerospace companies worldwide. The main settlements of Alenia are shown in figure 1. Each one is specialized for a

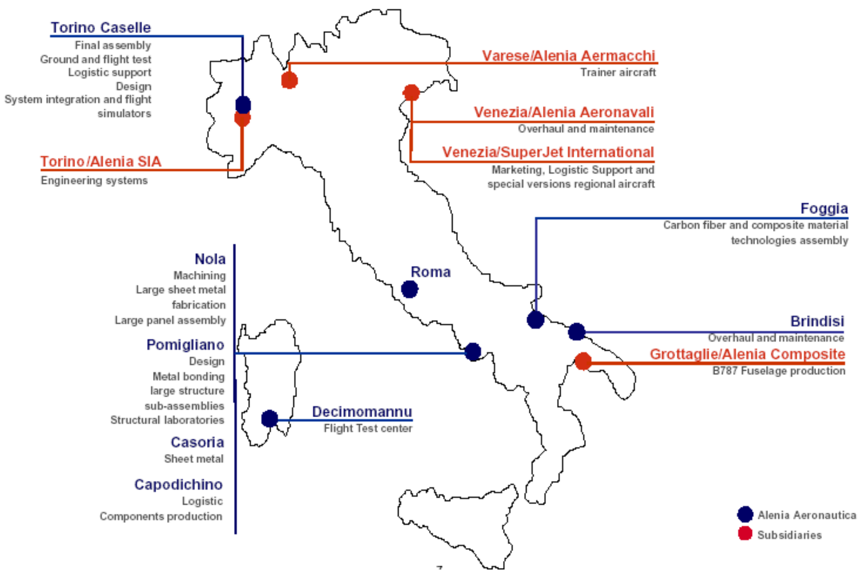

Fig. 1. Alenia Aeronautics establishments.

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process or a particular product.The business lines main programs include: Military Airlifters, Defense and Surveillance Aircraft, Regional Aircraft, Mission Systems, Aerostructures, Trainer Aircraft, Logistics and Maintenance Revision Operation (MRO) as figure 2, on page 4, shows.

2.1. *Alenia and Non-Destructive Inspection Controls*

Within the Alenia core activity a peculiar role is occupied by NDI. These controls can be used to process material parts and components in order to get confidence for their use, after the building stage, according to the original design criteria. In particular, NDI is finalized to:

- disclosure, localization, and evaluation of discontinuities, and all other types of imperfections;
- verify the integrity, the properties, and the composition of materials and components;
- measure the geometric characteristics of parts.

The nondestructive testing is a transversal area in the company, because it works during all phases of the life cycle of a part from design to maintenance. On page 5, figure 3 shows all the areas where the NDI works listing the main activities and highlighting the interconnections.

Among non-destructive testing methods, the most used are: Ultrasound Testing, PT, Radiography Testing, Magnetic Testing, Eddy Current Testing. They are used for production and in service inspection. An inspection method is unique compared to another for the type of material, the type of defect and the minimum size of the defect that the method can detect. The distinguishing characteristic of the main NDI controls are reported in table 1 on page 6.

The business rules with respect to international rules provide a periodic certification of all personnel involved in nondestructive testing for each method [1,2,14,9]. In particular, there are 3 Levels of certification - I, II, III: the Level I can process the inspection, the Level II can apply also the acceptance/rejecting criteria, the Level III can approve the inspection procedures and certify the personnel (see figure 3 on page 5).

3. Liquid Penetrant Testing

Liquid penetrant inspection of non-destructive testing is a process for finding discontinuities open to the surface in solids and non-porous materials [3]. In particular, by PT we can find the following kind of discontinuities:

- discontinuities originating on surface (e.g., cracks, see, on page 6, figure 4 frame a);

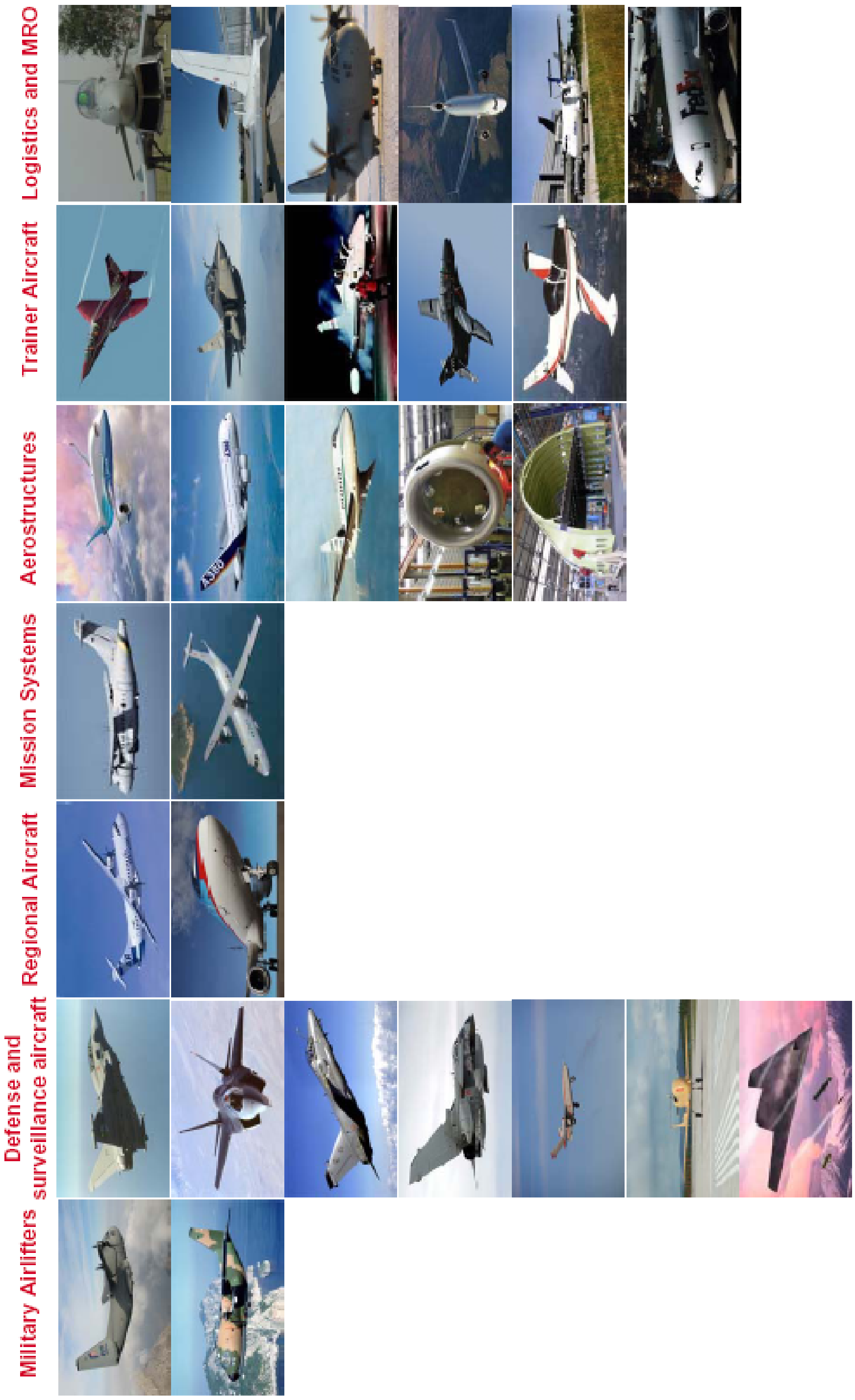

Fig. 2. Programs of Alenia Aeronautics company. MRO stands for Maintenance Revision Operation.

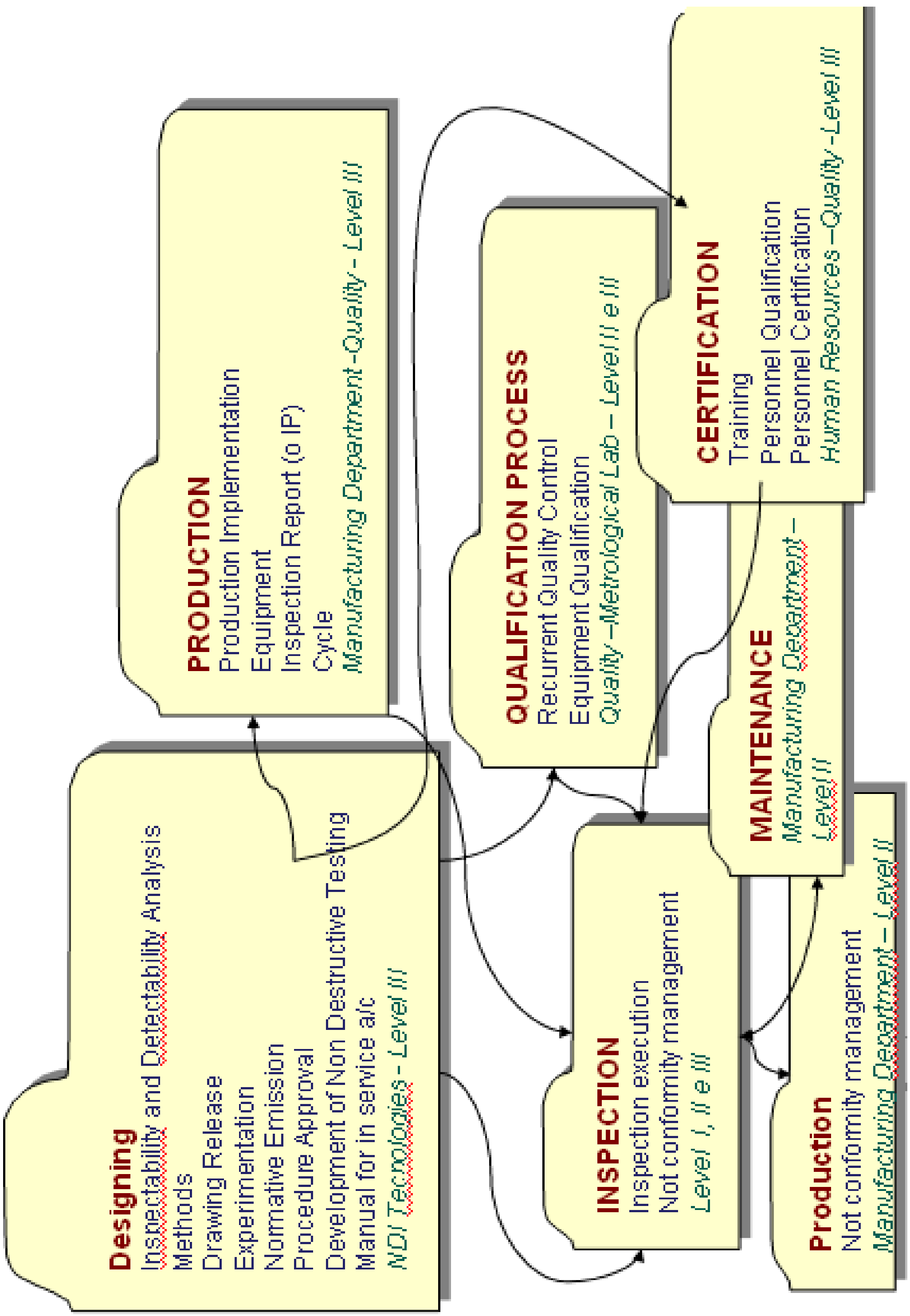

Fig. 3. Main activities of NDI area.

Table 1. Peculiarities of the main NDI methods: UT Ultrasound Testing, PT Penetrant Testing, RT Radiography Testing, MT Magnetic Testing, ET Eddy Current Testing. MRB stands for "if requested by the Material Review Board".

Method	Application Field	Materials	Detectability Defect Kind	Minimum Defect Size
UT	Production In Service	Composite Metallic	Internal	≈ 0.5 mm
PT	Production In service	Metallic Non Porous Materials	Open to Surface	≈ 0.01 mm
RT	Production In Service	Composite Metallic	Internal	≈ 1.0 mm
MT	Production In service	Ferromagnetic	Superficial Sub-Superficial	≈ 0.5 mm
ET	MRB In service	Metallic Conductor	Superficial Sub-Superficial	≈ 0.2 mm

- anomalies originating inside the material, but that propagate up to the surface (this is the case of a cavity within a melted part, see figure 4 frame b);
- anomalies open to the material surface due to the construction process (for instance: emerging porosity or porosity taken to the surface by a working machine, see figure 4 frame c).

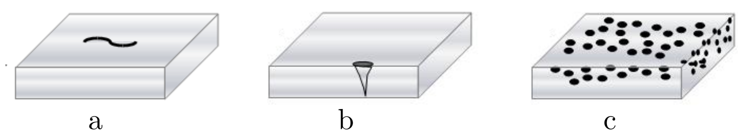

Fig. 4. Frame a: cracks, frame b: a cavity within a melted part, and frame c: emerging porosity.

The penetrant liquid is applied on the material surface (suitably cleaned). Then, it is necessary to wait for a suitable time so that the liquid owing to capillary action goes inside the discontinuities. Subsequently, we have a phase where the excess of liquid is removed from the surface. Finally, the penetrant which persists inside the cracks can be observed, in order to find and locate the presence of discontinuity. Henceforth, we have the following main phases:

- Application of penetrant.
  The penetrant liquid is applied on the surface where it enters on discontinuities or cracks (see figure 5).

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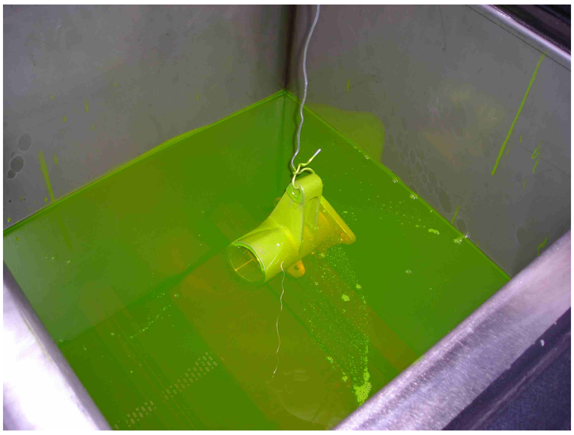

Fig. 5. Application of penetrant liquid.

- Removing the excess of liquid.
  At this stage, we perform a cleaning of the surface (e.g., with water) so that the liquid is left, practically, only inside the discontinuities open to the surface (see figure 6).

Fig. 6. Removing the excess of liquid.

- Inspecting.
  The penetrant contains a color component contrasting with the surface color: from a visual exam this allows to find the presence of discontinuities (see figure 7).

Indeed, PT is a more complex process, taking the following steps:

1. Cleaning.

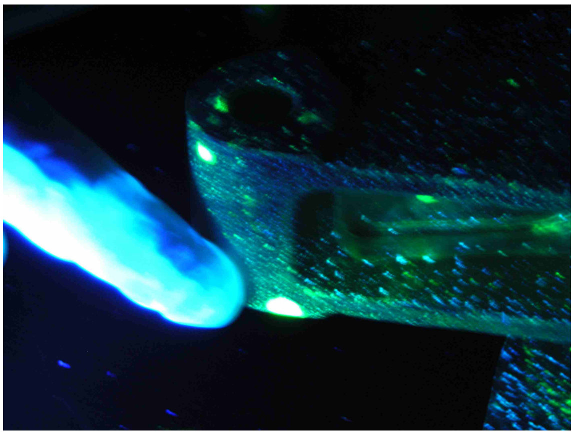

Fig. 7. Sightseeing the material part.

Requirement: all dirt has to be removed from the surface in order to allow a free action of the liquid penetrant within the occurring discontinuities.

2. Application of penetrant.
   Requirement: the penetrant liquid is applied on the surface where it enters on discontinuities or cracks. The application can be made in some different ways: brushing – usually applied with rags, cotton waste, or brushes; immersion – the entire part is dipped into a tank flood of penetrant; pouring – the penetrant is simply poured over the surface; and spraying – usually using a low pressure circulation pump or from pressurized spray cans. As far as the application by immersion is concerned, the *contact time* is defined as the immersion time plus the drainage time.
3. Removing the excess of liquid.
   Requirement: removing the excess of liquid from the surface, but in such a way that it will be present inside the discontinuities.
4. Application of a developer.
   Requirement: we use a developer to cover all the surface, usually some kind of porous material (like an absorbing coating). The aim of developer's application is to keep the penetrant track inside the discontinuity out for visual inspection.
5. Inspecting.
   Requirement: the penetrant contains a color component contrasting with the surface color: from a visual exam this allows to find the presence of discontinuities according to accepting/rejecting qualitative criteria.
6. Final cleaning.
   Requirement: cleaning the parts from the residuals of the inspection stuff.

In accordance with the requirements of AMS 2644 [16], the process of liquid penetrant inspection is classified for penetrant (Type, Method of removal, level of Sensitivity for fluorescent), the Developer (Form) and Solvent (Class) used. Table 2 shows this classification.

Table 2. Classification of penetrants Type, Method, Sensitivity, Developers, and Solvent.

Type	
Type I	Fluorescent dye
Type II	Visible dye
Method	
Method A	Water washable (oil-based)
Method B	Post-emulsifiable, lipophilic
Method C	Solvent-removable
Method D	Post-emulsifiable, hydrophilic
Method E	Water washable (water-based)
Sensitivity	(Only for Type I)
Sensitivity Level 1/2	Very low
Sensitivity Level 1	Low
Sensitivity Level 2	Medium
Sensitivity Level 3	High
Sensitivity Level 4	Ultrahigh
Developers	
Form a	Dry powder
Form b	Water-soluble
Form c	Water-suspendable
Form d	Non-aqueous for Type I fluerescent penetrant
Form e	Non-aqueous for Type II visible dye
Form f	Specific application
Solvent	
Class 1	Halogenated
Class 2	Non-halogenated
Class 3	Specific application

Type I penetrant are employed, almost exclusively, in aeronautics. All chemicals used within the PT process, but the cleaning steps, must generally conform to the AMS-2644 protocol [16] (i.e., the requirements are listed by QPL-AMS-2644 [15]). As far as non-metallic parts are concerned, it is prescribed to use penetrant of Type I, Method E, but for plastic phenolic materials or equivalent where it can be possible to apply all types of penetrant of Type I. Special care is required in order to verify the chemical compatibility between penetrant and acrylic plastics. Developers soluble in water (Form b) are not usually employed for penetrants cleneable by water (Method A). Some specific material allow only Form a and Form d. Developers of Form a are used, usually, only for penetrant of Type I. As far as non-metallic materials are concerned, the developers used are of Form

a. Chemicals used within the cleaning steps must conform to the technical applicable prescriptions.

All implants, apparatuses, and instrumentations have to ensure an accurate control as well as a suitable monitoring of the parameters involved by the process, providing a measurement inside the limits provided by the inspection procedure. In particular, minimum prescribed accuracies for the control and measurement of parameters related to the process are defined by Alenia technical norms NTA94151/-1 [6] and NTA94151/-2 [5].

4. Reserch activity

The relevant complexity of the PT process calls for a better understanding of the main steps involved. Since the planning and construction of physical tests are expensive and time consuming, it would be of paramount importance to develop mathematical and numerical models for the different stages of PT.

Within the above context, the first step was the formulation of a two-liquids one-dimensional mathematical model. With reference to figure 8, we look at a column of liquid 1, usually water, of fixed length ℓ_0 entrapped inside a horizontal cylindrical capillary of constant radius R and finite length L. At the left end of the capillary we have a reservoir filled with a penetrant liquid 2: ℓ is the moving liquid 1-liquid 2 interface coordinate. The differ-

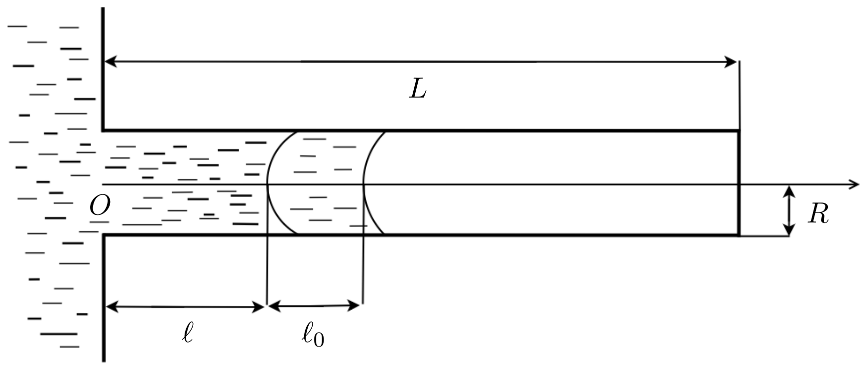

Fig. 8. Draft of a cylindrical capillary section.

ential equation governing the dynamics of the moving capillary is given by:

$$\frac{d}{dt}\left[(\rho_1\ell_0+\rho_2(\ell+cR))\,\frac{d\ell}{dt}\right]=2\frac{\gamma_1\cos\vartheta_1+\gamma_{12}\cos\vartheta_{12}}{R}-8\frac{\mu_1\ell_0+\mu_2\ell}{R^2}\frac{d\ell}{dt}\ . \tag{1}$$

In equation (1), $d\ell/dt$ can be interpreted as the average axial velocity, t represents the time variable, γ_1 and γ_{12} are the surface free energy for the liquid 1-air and the liquid 1-liquid 2 interfaces, and ϑ_1 and ϑ_{12} are corresponding menisci contact angles, ρ_1 and ρ_2 are the liquid densities, μ_1 and μ_2 are the dynamic viscosities of the two liquids, and $c = O(1)$ is the coefficient of apparent mass, that takes into account the flow effects outside the capillary. Moreover, for a closed-end capillary the entrapped gas action should be taken into account, by adding to the right hand side of equation (1) the terms

$$+p_a - \frac{p_a L}{L - \ell_0 - \ell} \, , \tag{2}$$

where p_a is the atmospheric pressure, and the second term is the entrapped gas pressure depending on the lengths involved.

In the last years, various studies have been carried out with several communications at international congresses: ICCMSE2006 (details at the URL: www.iccmse.org/ICCMSE2006/index.htm) [8], ICIAM2007 (URL www.iciam07.ch/index) [11] and SIMAI2008 (URL: www.iac.rm.cnr.it/simai/simai2008/index.htm) [4,12,10,13], ending up with the above model formulation, see [7].

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