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Fluid Contamination Aspects Due to Hydraulic System Operation

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***Abstract:** Fluid contamination is a significant concern in hydraulic and fluid systems, as contaminants in hydraulic, lubrication, or process fluids lead to equipment wear, corrosion and even catastrophic failures in sensitive equipment. Effective contamination control is essential for maintaining system reliability, optimizing performance and extending the life of both fluids and equipment. With advances in sensing, modelling and filtration technologies, industries are better equipped to manage fluid contamination and ensure system resilience. This paper presents the fluid contamination general aspects, main sources, the principal contaminants types, represented by different particles of solid contaminants (metallic fragments, dust and wear particles from machinery components) and its implications for system efficiency. The contaminant particles can be abrasive and cause wear on surfaces, water droplets often found in hydraulic and lubrication systems, leading to corrosion, degradation of additives and further reduced fluid operational performance, other air and gas particles entrained into hydraulic fluid volume leading to cavitation, reduced lubrication and oxidation. Main models describing the hydraulic fluid contamination are presented and further the numerical analysis results based on parameters primary considered for a hydraulic actuation type.*

***Keywords:** Hydraulic actuation, fluid contamination, contaminant types, mathematical model, numerical analysis*

1. Introduction

The degree of cleanliness of the working fluid is an essential condition for the optimal functioning of hydrostatic drive systems, as it ensures that the tasks imposed on the respective system are strictly fulfilled.

The general aspects of fluid contamination, its sources and its implications is shown through the principal contaminants types, which are represented by different particles of solid contaminants (metallic fragments, dust and wear particles from machinery components), that can be abrasive and cause wear on surfaces, water droplets often found in hydraulic and lubrication systems, leading to corrosion, degradation of additives and further reduced fluid operational performance, other air and gas particles entrained into hydraulic fluid volume leading to cavitation, reduced lubrication and oxidation. Other contaminants include chemical contaminants like acids or solvents that act to fluid properties degradation, corrosion of metal components, or react with additives.

Manufacturing residual material particles which are leftover from the manufacturing process are contaminants represented by metal shavings, dust, or paint remnants.

From the external environment contaminants are accounted all dust and dirt that enter the fluid system through seals, open reservoirs, or vents.

Over time, components such as seals, bearings and pumps generate wear particles that mix with the fluid. Also, from system maintenance activities could be introduced contaminants through improper maintenance or during refilling and topping off, while water ingress can be mainly from condensation, leaks, or improper storage of fluids.

Regarding the effects of contamination, it is demonstrated that abrasive particles generate erosion and surface wear on moving parts, leading to reduced lifespan of components. Water, acids and other contaminants cause corrosion, weakening metal components and compromising seals. Entrained air or gas bubbles can cause cavitation phenomenon, which damages pump surfaces and reduces efficiency. Fluid properties like viscosity, lubrication and heat transfer can be compromised, resulting in a drop in system performance and over time, excessive contamination can lead to clogging, component malfunctions, or even complete system failure.

It is therefore important to carry out specific measurement and analysis of contaminants, especially particle counting methods, as the main method for assessing contamination levels, as they measure the size and quantity of particles in the fluid.

Based on ISO cleanliness codes as standards, the number of particles per milliliter of fluid is classified, allowing systems to maintain specific cleanliness standards.

It is also important to measure water content using techniques such as Karl Fischer titration or relative humidity sensors that are used to measure water contamination.

Spectrographic analysis to identify specific contaminants or wear metals, especially in lubricating oils, is also a handy method.

Testing the viscosity and pH of the working fluid helps to establish the condition of the fluid when the chemical composition of the fluid has changed due to contamination.

In order to avoid contamination of the working fluid of the hydrostatic system, filtration activities of the working fluid are necessary through

filtration systems. These are presented as different types of filters (screen, depth, magnetic) that can retain and remove particles from fluid. Good filtration removes even microscopic particles but may slow fluid flow.

For water retention and removal, methods like vacuum dehydration and centrifugal separators are used.

At the level of breathers and seals, in order to prevent external contaminants, systems use breathers, seals and gaskets that protect against dirt and moisture.

Regular fluid testing and monitoring systems have the role of detecting fluid contamination early, allowing for preventive maintenance.

Using proper design standards and implementing protocols for flushing, cleaning and preventive maintenance, good results are obtained in terms of reducing contamination risks.

Standards and Guidelines that provide detailed information on hydraulic fluid contamination are mainly represented by ISO 4406 as a widely used standard for cleanliness codes in hydraulic systems, which define the allowable particle counts per milliliter, ISO 4407 which outlines particle count methods using microscopic techniques and also ASTM Standards which provide guidelines on water and particle contamination measurement and acceptable limits within hydraulic fluids.

Implications for Different Industries that use hydraulic systems to operate multiple equipment working parts should be mentioned as the main domains represented by aerospace and defense because fluid high cleanliness is essential due to the sensitivity of hydraulic components and the critical nature of equipment reliability.

Further within automotive and heavy machinery it should be highlighted that hydraulic and lubrication fluids must be kept clean in order to prevent wear in engines, transmissions and hydraulic pumps.

The Oil & Gas energy industry has high needs for fluids used in drilling and extraction face challenges from abrasive particles, water ingress, and microbial growth.

For food and pharmaceuticals there are strict requirements regarding contamination control as fluids interact with food products, requiring non-toxic, contaminant-free fluids.

Future developments in hydraulic fluid contamination control mean the use of intelligent systems that include smart sensors that have the role of monitoring fluid quality in real-time, transmitting data to control systems that alert operators when contamination levels are too high.

We are moving towards achieving a high level generically called advanced filtration technologies (AFT) which uses new filter materials and designs that improve efficiency and reduce the need for frequent filter changes, including the possible use of nano-additives and self-healing fluids, as types of fluids containing nano-additives that can bind to contaminants or heal small abrasions caused by contaminants [1-10].

2. Fluid Contamination Modelling

For contaminant transport models the Lagrange and Euler methods are primary used to simulate contaminants distribution within fluid systems. Each method has a unique perspective on how particles or contaminants move through the fluid field and each is suited to different types of analyzes in fluid dynamics, including hydraulic and lubrication systems.

For high filtration efficiency, mathematical models are used to calculate the filters impact on removing particles, tracking efficiency over time and across different filter types [11-15].

Numerical analysis enhances the dynamic simulation performance that accounts for factors like temperature, wear rate and filtration efficiency, making it possible to predict contamination build-up and the impact on performance based on the results obtained.

The LAGRANGE method approach, presents a perspective in which individual particles (contaminants) are tracked as they move through the fluid. Each particle's position, velocity, and other properties are followed over time, essentially "traveling" along with the contaminant in the fluid flow.

The approach is intuitive because it mimics how a contaminant might be observed if one could track its exact path through the system.

For a particle of mass *m* and velocity *v(t)* the Newton second law is written as:

$$m\frac{dv}{dt}=\sum F$$

$$\sum F = F_d + F_g + F_b + F_l + F_f \tag{1}$$

where the main forces acting on the particle are considered as drag force *(Fd)* directly dependent of drag coefficient *(Cd)*, gravity force *(Fg)*, buoyancy force *(Fb)*, lift force *(Fl) based on* lift coefficient *(Cl)* and other forces *(Ff)* represented by hydrodynamic, Van der Waals, electrostatic repulsion forces, steric and contact (elastic and frictional) forces.

$$F_d = -\frac{1}{2} A \cdot C_d \cdot \rho \left| v-u \right| \left(v-u \right)$$

$$F_g = mg$$

$$F_b = -\rho \cdot g \cdot V_p \tag{2}$$

$$F_l = C_l \cdot \mu \sqrt{\rho \cdot \nu} \cdot D_p^2 \frac{\left(u-v \right) \times \nabla \times u}{\left| u-v \right|}$$

Each contaminant particle is tracked individually, showing its path and changes in velocity, pressure, and other variables over time, while it focuses on individual particles or "parcels" of fluid, capturing the transport of contaminants due to advection, diffusion and other forces acting on each particle.

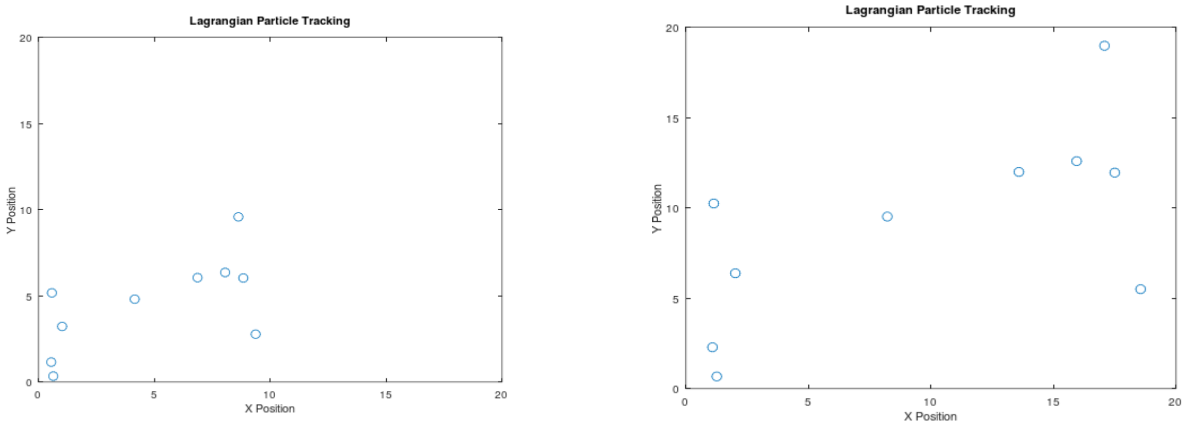


Fig. 1. The time distribution of particle tracking based on Lagrange method

The position of each particle *x(t)*, is updated by integrating the velocity over time:

$$v(t) = \frac{dx}{dt} \tag{3}$$

The method allows for precise modeling of particle-fluid and particle-particle interactions, such as collision, aggregation and deposition.

The main advantages offered are related to the fact that it offers highly detailed insights into the behaviour of individual particles which is useful for studying contaminant behaviour in complex flows.

The method capture localized phenomena such as particle sedimentation, aggregation and specific particle-fluid interactions.

Also, in terms of temporal and spatial details, is effective for applications where understanding the detailed trajectory of particles is essential, especially for particle deposition on surfaces or contamination hotspots.

The EULER method approach treats contaminants as a concentration field rather than individual particles. Hence, the fluid domain is divided into fixed control volumes or grid cells, and the contaminant concentration within each cell is calculated over time.

The focus is on how the contaminants concentration changes at fixed points in space due to advection, diffusion and reaction rates within the fluid.

The field-based approach has the ability to model contaminant concentration as a scalar field that varies with position and time, rather than tracking individual particles [8-17].

A fixed reference frame calculates contaminant transport at specific points in space, focusing on how contaminants diffuse, mix, and spread within the fluid field.

The contaminant transport is modelled as a concentration field *C(x, y, z, t)* within the fluid region. The main approach uses the advection - diffusion equation which describes the contaminant evolution at fixed spatial points:

$$\frac{\partial C(x,y,z,t)}{\partial t} + u\left(u_x,u_y,u_z\right)\cdot\nabla C(x,y,z,t) = D\nabla^2 C(x,y,z,t) + S(x,y,z,t) \tag{4}$$

where:
C – contaminant concentration field;
u – fluid velocity vector;
D – diffusion coefficient;
S – source or sink term for contamination sources or filters.

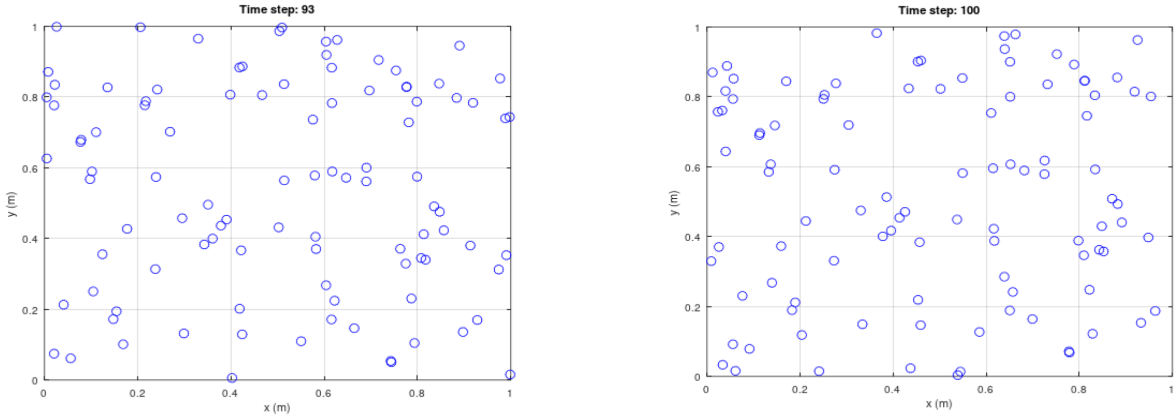


Fig. 2. The time distribution of particle tracking based on Euler method

As presented in figure 3, the Euler method provides a continuous view of contaminant concentration, while the Lagrange method gives specific details about individual particle movement, which is valuable for both density observation and particle tracking in fluid contamination approaches.

The continuum approach that assumes a continuous contaminant distribution is highlighted, which is particularly useful for high-density contaminant flows.

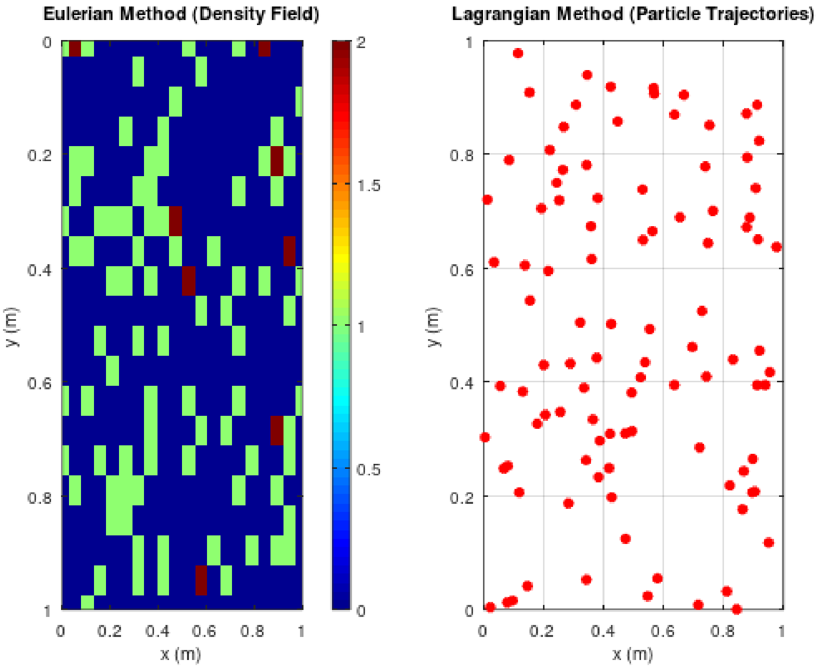


Fig. 3. The spatial distribution of particle tracking based on both Lagrange and Euler methods

The main advantages are related to the efficiency offered for large-scale systems, being suitable for large, complex systems with high concentrations of contaminants, as it avoids tracking individual particles. The improved computational efficiency is offered for high-contaminant densities or turbulent flows, as it works with averaged values rather than individual particle data.

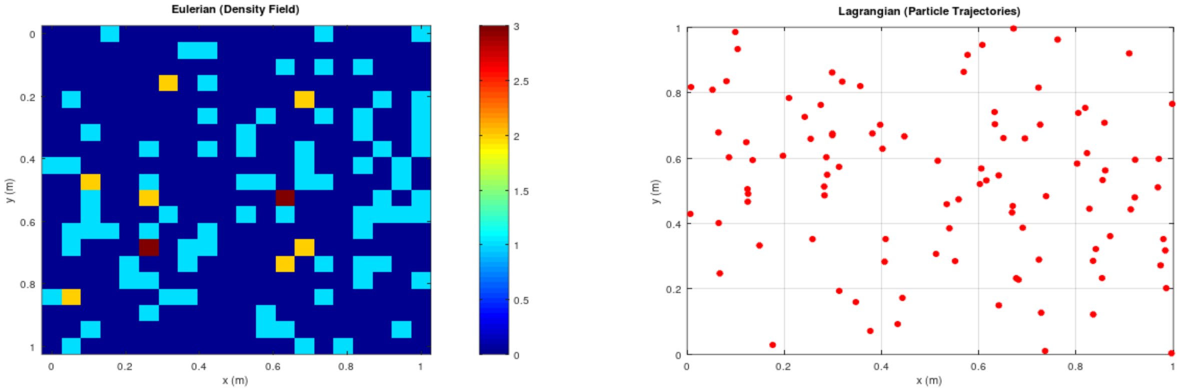
The Euler method is effective at simulating processes like diffusion, convection and mixing where concentration changes are smooth over space and time, for the specific applications concerns like general contamination analysis, being mainly used for studying overall contaminant dispersion and concentration within hydraulic systems and predicting contaminant buildup over time, ideal for applications where diffusion and mixing are the main transport mechanisms, such as in large reservoirs or cooling systems and also useful in systems where contaminants are uniformly dispersed and specific particle trajectories are not critical to the analysis.

3. The hybrid Euler-Lagrange approach

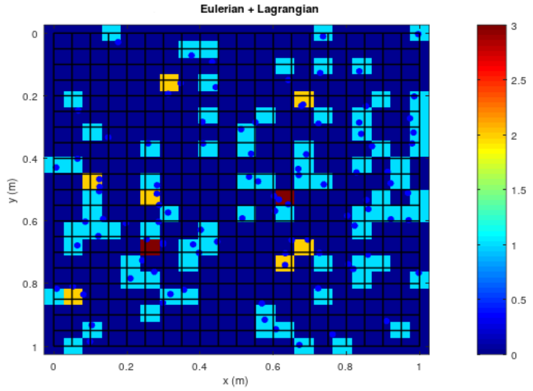
In fluid dynamics and contaminant transport applications different models are used which combine the two methods (Euler, Lagrange) in order to take advantage of the strengths of each approach. In the case of fluid contamination modelling, this approach often seeks to balance between computational efficiency and accuracy, particularly when dealing with complex flow fields, heterogeneous contaminant transport, or both.

In the concept of the hybrid approach Euler-Lagrange method combines aspects of both methods related to existence of fixed grid points used to solve for the flow or concentration at different spatial locations, which is typically more computationally efficient for solving large-scale problems (Euler method), while individual particles or tracers are tracked as they move through the flow region, capturing detailed dynamics of individual particles, which is ideal for studying individual particle behaviour or precise tracking (Lagrange method).

In this approach, the Euler method models the continuous fluid field, while the Lagrange method tracks individual particles. The particles are registered according to the fluid flow and the contaminant concentration is updated in the Euler grid. This method is especially useful for tracking discrete contaminant particles (water droplets or particles in the fluid) in a flow field.



a) Euler concentration grid b) Lagrange individual particles



c) The combined view

Fig. 4. The spatial distribution of particle tracking based on hybrid approach (Lagrange and Euler methods)

The particles movement is calculated in the Lagrange frame and further their concentration is added to the Euler grid.

Figure 4a presents the density of contaminant particles mapped into fixed grid (Euler), where according to the legend the higher particle concentration is shown, enhancing in this manner the macroscopic contaminant distribution. In the 4b figure all individual Lagrange particles are shown with specific distribution.

This hybrid approach captures both the global distribution of contaminant (Euler) and the individual contaminant particles motion (Lagrange).

4. Numerical analysis for fluid contamination

A numerical approach analysis which simulates the contaminant transport within a fluid system is performed, incorporating a few additional physical parameters, represented by fluid flow velocity, particle size and filtration efficiency according with particle size (figure 5).

For hydraulic actuation systems, filtration efficiency versus particle size represents the critical aspect for maintaining the system reliability and performance over time. All contaminants such represented by dust particles, wear particles or water can severely damage the hydraulic circuit components.

The hydraulic filtering units are designed to capture particles of varying sizes, typically in the range of 1–100 micrometers (µm), while the filtration efficiency is defined as the fraction of particles removed, which is highly dependent on the filter beta ratio *(β)* and particle size.

The beta ratio *(β)* is used to describe the filtration performance, while the β=2 means 50% efficiency (1 from 2 particles is removed) and further β=200 means 99.5% efficiency (199 from 200 particles are removed by the filtration system).

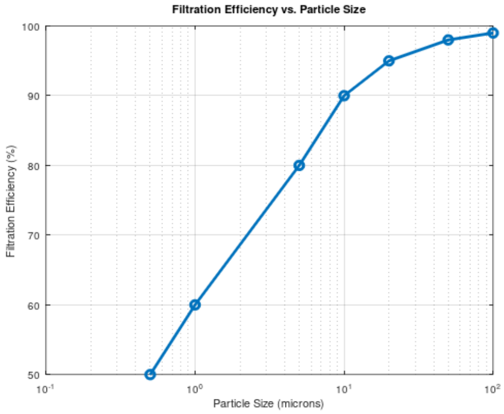


Fig. 5. The filtration efficiency according with the particle size (microns)

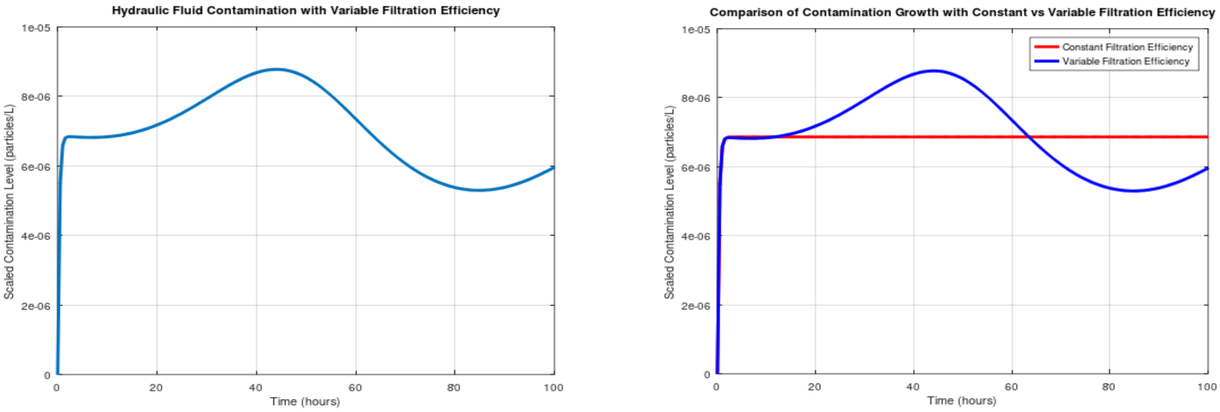
The study highlights the different conditions with impact on the contaminant’s concentration and the system behaviour over time.

Table 1. Numerical initial values

Crt. No.	Parameter	Value	
1.	Fluid domain length	1.00 (m)	
2.	Fluid flow velocity for x and y coordinate components	u=0.1 m/s	v=0.05 m/s
3.	Filtration efficiency	50 – 99 %	
4.	Number of particles	100	
5.	Analysis time steps	100	
6.	Particle size distribution	Equal size	
7.	Particle initial position	Random distribution	

Regarding the particle movement, it is considered that are entrained by the flow (Euler velocity field).

The filtration system removes particles according with filtration capacity, while the contaminant particles of constant size are in motion influenced by the fluid velocity field.



a) Fluid contamination due to variable efficiency filtration system

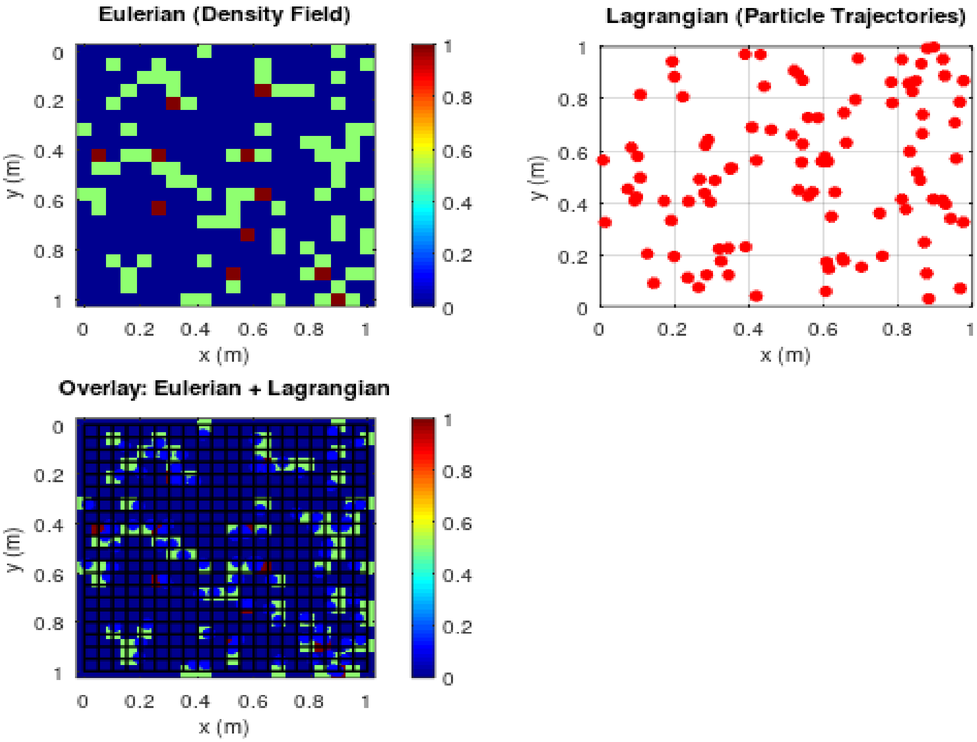
b) Fluid contamination due to constant and variable efficiency filtration system

Fig. 6. The hydraulic fluid contamination function of constant and variable filtration efficiency

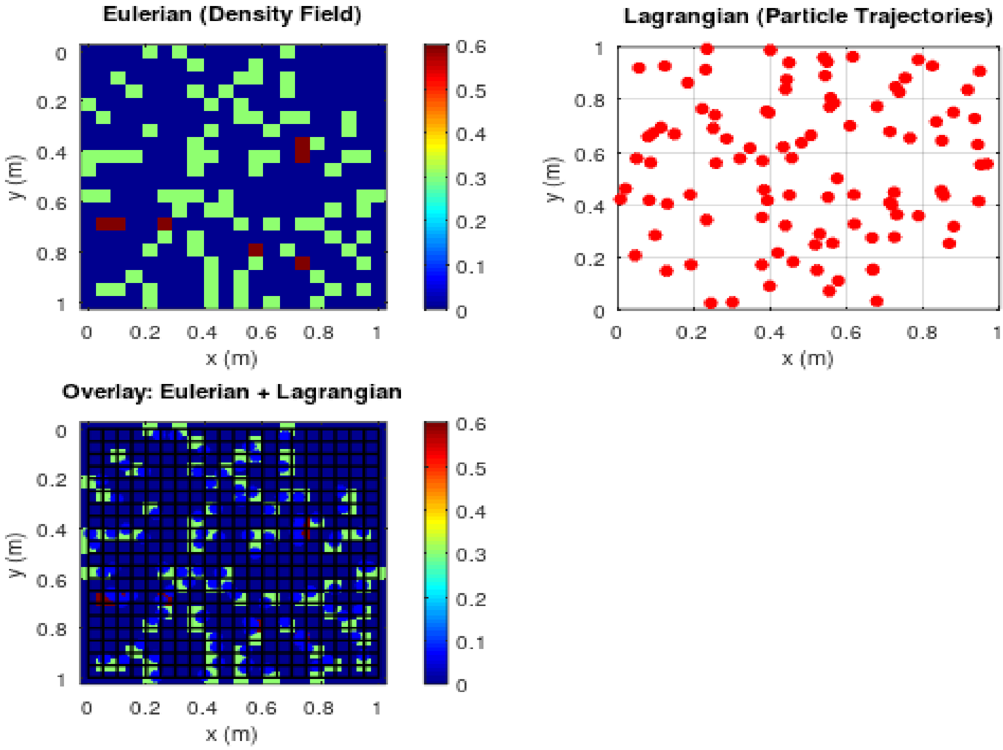
For moving particles using Lagrange method is tracked the position, according with the Euler grid interactions. The contaminant concentration is calculated at each grid cell and further updated in time. The filtration system enhances the particle concentration reduction over time, with proportional influence of filtration efficiency value. Filtering solutions with constant (theoretical) and time-variable efficiency (real condition) are highlighted in Figure 6.

The analysis results will emphasize the particle concentration field over time and contaminant dispersion and accumulation at the fluid region over time.

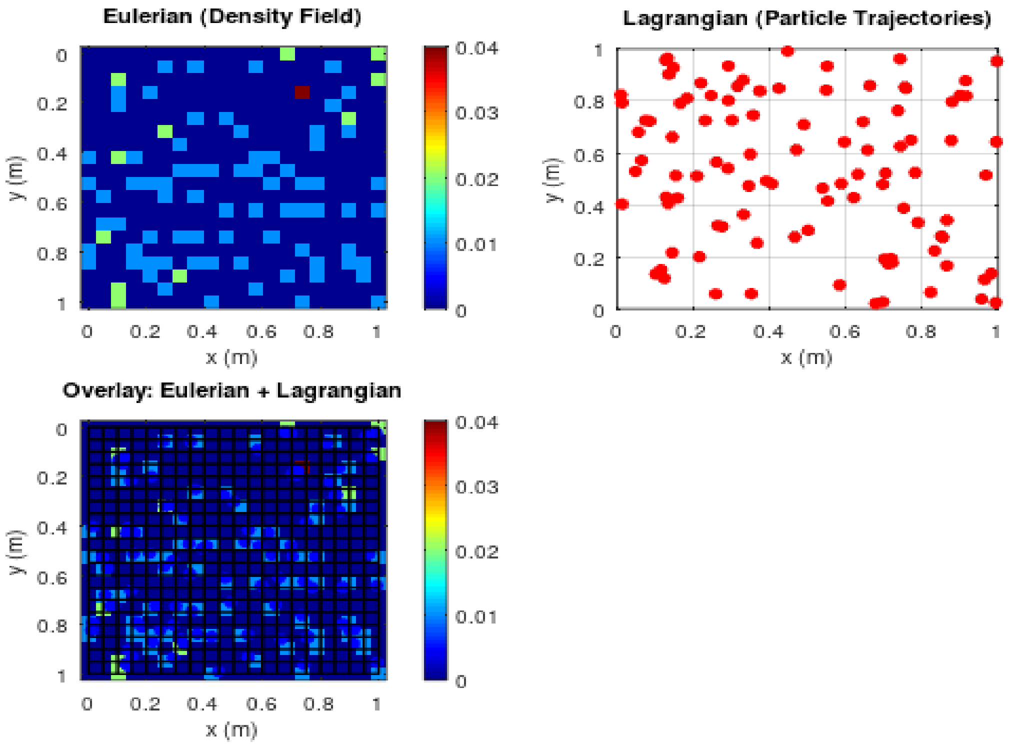
The obtained results are presented in figure 7, being emphasized the fluid flow



a) Filtration system efficiency of 50 %



b) Filtration system efficiency of 70 %



c) Filtration system efficiency of 99 %

Fig. 7. The particle contaminant dispersion concentration field and accumulation at the fluid region over time based on hybrid approach with different filtration efficiency values

As shown on the obtained results the concentration of contaminant particles is drastically reduced in the case of analysis corresponding to the high values of the efficiency of the filtration system as observed in figure 7.

The specific diagram for contaminant concentration according with filtration efficiency is presented in figure 8 highlighting the major differences obtained by the analyzed cases with specific values declared.

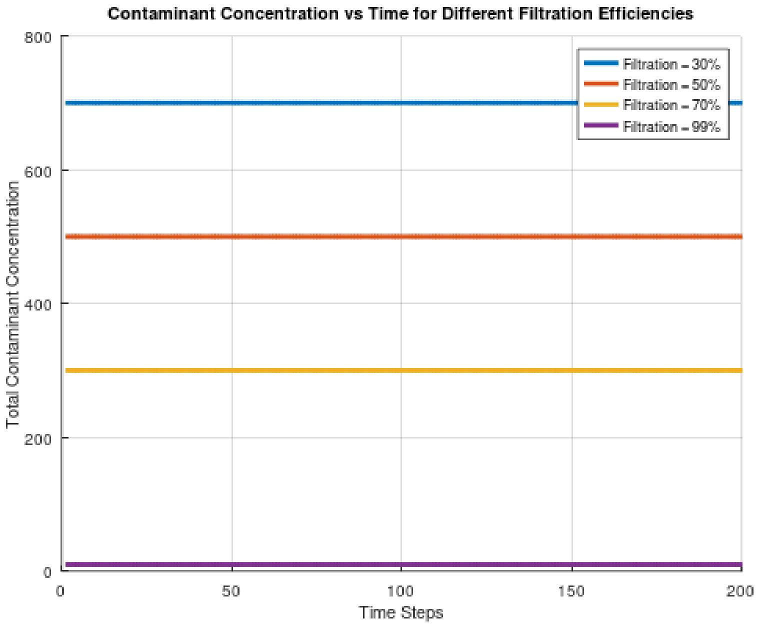


Fig. 8. Contaminant concentration versus time steps due to filtration efficiency range

Based on the results obtained from the numerical analysis performed, it can be observed the particular importance of the filtration system action on the cleanliness of the working fluid which must be at an upper limit in order to obtain the best operation results for the hydraulic system. Based on the specific analysis methods, the situations of specific concentrations of contaminant particles were identified and how they can be removed as a result of the action of the filtration system operating at different efficiency values, resulting from this the importance of permanently ensuring a high filtration efficiency, as an essential condition to be applied in order to ensure the optimal operating conditions of the hydrostatic system serving a certain work equipment.

5. Conclusions

Fluid contamination in hydraulic systems arises from a variety of sources, both internal and external, during system operation.

Contaminants directly affect the system performance, reduce component lifespan and further increase the maintenance costs.

The present paper presents the modeling approach using the Euler and Lagrange methods widely used in fluid mechanics and for contamination analysis enhancing the contaminants motion, dispersion and interactions with hydraulic fluid systems.

As shown in the paper, each method presents a unique perspective on how particles or contaminants move through the fluid region, each method being suited for different analyzes types in fluid dynamics field, including hydraulic and lubrication systems.

The Euler method focuses on fixed points in space, monitoring the fluid properties like velocity, pressure and contaminant concentration, as they change over time. The main advantages are related by analyzing large-scale contamination behavior, being well-suited for steady-state and continuous-flow scenarios and representing a simpler computationally method for systems with fixed geometries.

The Lagrange method tracks individual particles or fluid elements as they move through the system, following their trajectories over time and provides detailed, particle-level insights, captures localized effects, such as particle deposition and wear, being ideal for transient (time-varying) contamination events.

In practical contamination analysis, Euler and Lagrange methods are often used together, as hybrid models. In this manner the Euler model describe the overall flow field and contaminant concentrations, while the Lagrange model track the specific particles for detailed insights.

It is emphasized the practical importance within the hydraulic systems regarding special design optimization, while through Euler model is optimized the filter placement and flow paths for efficient contaminant removal.

For wear and damage prediction the Lagrange model provide a proper prediction on where the particles will be accumulated and further could cause wear.

As the hydro static system operation requires real-time monitoring, both methods support advanced diagnostic tools, represented by numerical analysis approaches for simulations, in order to predict the contamination risks and improve maintenance schedules.

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