USE OF TRIZ SU-FIELD MODELS IN THE PROCESS OF IMPROVING THE INJECTOR OF AN INTERNAL COMBUSTION ENGINE

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Abstract: The article describes a method for analyzing and solving problem situations with the use of Su-Field models and 76 inventive standards. These tools are part of the "Theory of Inventive Problem Solving". The author has presented the basic concepts of Su-Field models, including in the compilation of the most commonly used substances their fields and types of interactions in Su-Field models. The inventive standards have also been presented and grouped. Attempts have been made to solve two undesirable situations that occur during the operation of a complex technical system, which is the fuel injector of the self-ignition engine. Problem situations related to insufficient impact were modelled – too low tightening of the injector spring, and negative (harmful) interaction – erosive wear of the holes in the atomizer nozzle. Using the inventive standards of Class-1 and Class-2, general solutions to these problems have been found. After the transformation, exemplary detailed ways of solving the aforementioned problems have been presented in order to improve the design of the injector for these models. A summary and comments on the applicability of the presented methodology, regarding such complex technical systems, have also been presented.

Keywords: Theory of Inventing Problem Solving – TRIZ, Su-Field model – SFM, inventive standards – IS, fuel injector, diesel engine

1. INTRODUCTION

Since the middle of the last century to the present day, there has been significant development in many interdisciplinary fields of knowledge such as systemics, cybernetics, praxeology, bionics, heuristics and inventics. This last branch of science deals with creative processes, and more specifically, the development of methods that improve creative thinking. One of the most prominent representatives of this discipline was Gienrich Altshuller (1926-1998), who in 1946 began his work on creating an invention algorithm (Boratyński, 2009), later named ARIZ, which is an abbreviation of the Russian name Алгоритм Решения Изобретальских Задач (Algorithm of Inventive Problems Solving). In the following years, Altshuller perfected the algorithm by developing its subsequent versions. At the same time, together with his colleagues, he developed a number of auxiliary methods, which could finally be closed in a broad concept known as TRIZ, from the Russian Теория Решения Изобретательских Задач, i.e. "Theory of Inventive Problem Solving". TRIZ is a complex methodology which includes many tools used to identify the problem, search for solutions and make the final selection and evaluation of these solutions (Chybowski, 2017a). With time, the original inventive issues have been extended to include non-engineering issues, including e.g. social, business and marketing problems. TRIZ has significantly contributed to the development of many economies (Chybowska et al., 2018) and, thanks to its high efficiency, in the creation of innovative solutions. In 1973 Altshuller introduced Su-Field analysis (short for Substance-Field, also referred to as S-F, SFM, and S-Field) to TRIZ and in 1975 he developed inventive standards (Gajewski, 2013). Su-Field analysis is used to model and solve problem situations (Wu, 2011).

The use of abstract Su-Field operators, instead of working on "the real problem", enables quick modelling of a problem situation (in TRIZ described as conflictual, due to the fact that, according to TRIZ, problems are analyzed in the form of their physical/technical contradiction). This model allows for the minimization of the so-called psychological inertia limiting the analyst in connection with his/her habits and fixation on the established state of affairs (Chybowski, 2017a). The TRIZ model of problems solving, which is based on the paradigm of generalization (abstraction) of the situation and its refinement (instantiation) has been presented in Figure 1. This is due to the detailed presentation of the problem situation using the general model elements in the form of a field (fields) and substances (objects, elements, materials). For a generalized Su-Field model, a generalized Su-Field solution is sought. The final solution to the problem is obtained by re-detailing the overall solution to form a detailed solution, which is related to the analyzed and resolved problem.

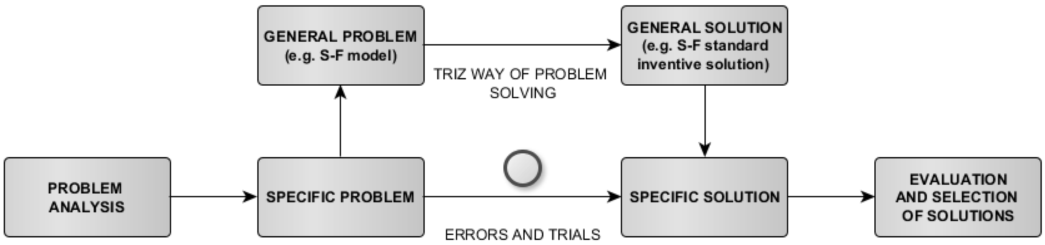

Fig. 1. A TRIZ model of problems solving with an example of the use of SU-FIELD models

Su-Field models and standard inventive solutions can be used as independent tools, as well as elements of more elaborate methodologies (Boratyński, 2009), such as those commonly accepted by the majority of Altshuller's heirs, for example the version of the 1985 invention algorithm designated ARIZ85C, where the Su-Field models are used in Part 4 of the algorithm (Altshuller, 1985). Further on in this article the essence of how to build Su-Field models and a case study on the application of the aforementioned methods in the process of refining the piston fuel injector of an internal combustion engine with self-ignition has been briefly presented.

2. METHODOLOGY

According to the definition adopted in TRIZ, the Su-Field model of a minimal technical system consists of two substances and a field that interacts with them, whilst all these elements must be associated with a minimum of two relations. The incomplete system consists of only some of the listed elements (Fig. 2 a-c), and for its development it must be extended to the full model (Fig. 2d). The presented transformation from the incomplete system to the Su-Field minimal is carried out with a standard inventive solution, designated in the literature as 1-1-1 (Livotov and Petrov, 2013). As a result of the development of the technical system, the Su-Field mapping models are subject to modification, addition or removal of constituent substances or fields, e.g. by creating chain models (Fig. 2e – IS 2-1-1) or by dual Su-Field (Fig. 2f – IS 2-1-2) (Livotov and Petrov, 2013).

As was mentioned above, the minimum Su-Field model consists of two substances and a field. Depending on the level of detail of the analysis and its subject, these substances are either physical or abstract elements of the technical system under consideration, including subsystems, machine elements or devices, but also sets of fields of homogeneous or heterogeneous material. Table 1 has listed examples of substances that can be subjected to Su-Field analysis.

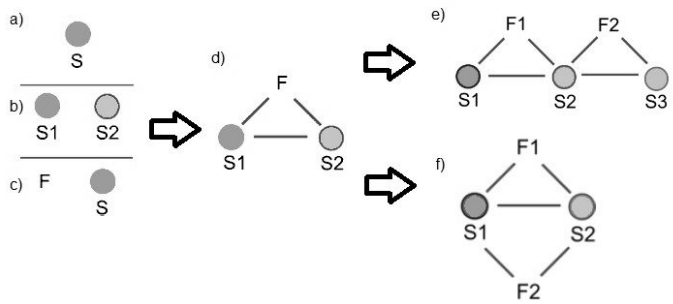

Fig. 2. Examples of Su-Field models: a) – c) – incomplete models, d) – a full Su-Field model, e) – a chain Su-Field, f) – a dual Su-Field; S, S1, S2, S3 – substances, F, F1, F2 – fields

Table 1
The list of exemplary substances used in Su-Field analysis

Types of substances		
States of substance	Transformable substances	Other substances
• Aerosol • Elastic • Emulsion • Foam • Gas • Gel • Granulated • Liquid • Paste • Perforated • Plasma • Porous • Powdered • Suspension	• Boiled • Condensed • Dissolved/crystallized • Evaporated • Explosive • Flammable • Gas-generating/absorbing • Hardened • Heat generating/ absorbing/ accumulating • Liquid-generating/absorbing • Melted • Mixed/composed/decomposed • Piezoelectric • Polymerized / de-polymerized • Products of dissociation/recombination • Sublimated • With Curie Point • With shape memory	• Adhesive • Bimetallic • Changing color • Changing electrical resistance • Chemically active • Conductive • Dielectric • Easily breakable • Easily removable • Electrorheological fluid • Ferromagnetic • Luminescent • Magnetic solids/powders • Photochromatic • Photosensitive • Semiconductive • Transparent • With low or high friction • X-ray sensitive

Source: (Invention Machine Corporation, 1988; Souchkov, 2016).

According to TRIZ, a field is the effect that it has on an object (substance). This effect changes or maintains the properties of the object. According to the VDI standard (Verein Deuche Ingenieure, 2015), 5 basic fields have been distinguished in TRIZ which are: mechanical, acoustic, thermal, chemical and electro-magnetic. In the literature many specialists have accepted 8 basic fields marked MATChEMIB for short, which are (Mayer, 2017): mechanical, acoustic, thermal, chemical, electrical, magnetic, intermolecular and biological. However it should be noted that the definition of fields includes interactions which are not considered such in physics, whereas others have been reduced to a common group. In physics only 4 basic interactions are distinguished: strong, electromagnetic, weak and gravitation. In TRIZ gravity is reduced to one group of interactions – the so-called mechanical fields – expressing physical interactions between elements in a broad sense, which from a physical point of view are not fields, including such phenomena as friction, erosion, etc. In turn sound (acoustic field), which is a mechanical wave, is included in TRIZ as a separate group for pragmatic reasons. The same applies to thermal, biological and chemical effects, which, although they theoretically can be reduced to basic physical interactions due to the convenience of using many problems in the description of these phenomena, were included in TRIZ as separate fields. Individual types of fields can be detailed depending on the specific needs, the subject and the purpose of the analysis. Table 2 has presented sample fields that can be used in the construction of Su-Field models.

Table 2
A summary of the sample fields used in the SU-FIELD analysis

Types of fields and forces			
Mechanical Fields	Electromagnetic fields	Other fields	Field Dynamics
• Acoustic vibrations (oscillations) • Buoyancy • Coriolis forces • Centrifugal forces • Diffusion • Elasticity • Friction forces • Gravity forces • Inertia • Infra-sound • Internal tension • Lifting forces (lifting) • Mechanical vibrations (oscillations) • Osmosis • Pressure of liquids and gases • Sound • Thermal tension • Ultrasound	• Coherent light (laser) • Electric current • Electric discharges • Electromagnetic field • Electron beam • Electrostatic field • Foucault currents • Infrared waves • Magnetic field • Microwaves • Radio waves • Skin current • Ultraviolet rays • Visible light • X-rays	• Biological • Chemical reactions • Cooling • Heating • Informational • Nuclear forces • Odor • Taste • Thermal shock	• Amplification • Damping • Expansion • Field gradient • Filtering • Focusing • Interfering • Oscillation • Pulsation • Reflection • Refraction • Resonance • Scanning • Scattering • Shielding • Single wave • Standing wave • Structuring • Traveling wave

Source: (Invention Machine Corporation, 1988; Souchkov, 2016).

Between the field and the substances in the Su-Field models, one or two-way relations are specified. There may be no relationship between specific elements. In addition, there may be more than a single interaction between two elements. For instance, two or more positive or negative effects can occur at the same time and/or in the same space. A summary of the main relationship designations in Su-Field models with examples has been shown in Table 3.

Table 3.
A summary of the main relationships in Su-Field models

Description	Symbol			Example
	General	Action	Interaction	
Useful (positive)				supports Bedplate  engine
Harmful (negative)				emits Engine  greenhouse gas
Insufficient				cools Air cooler  scavenge air
Excessive				resides on Lube oil  engine block
Poorly controlled				Welds Machine  Aluminium
Not present (missing)	No connection between elements at given time or space			Engineer Instruction

Altshuller developed 76 inventive standards (IS). In the extended versions of the standards of other authors, their numbers have reached 111 (Russo and Duci, 2015) and even higher.

However practice has shown that 76 standard solutions are sufficient to find resolutions for most problems. A synthetic combination of these standards has been included in Table 4.

Table 4
The list of Altshuller's 76 inventive standards

Class	Subclasses		General Description	Remarks
1			Synthesis and decomposition of Su-Field (13 standards)	
	1-1		Synthesis of Su-Field	
		1-1-1		Creating a new interaction
		1-1-2 – 1-1-5		Improving effect of insufficient interaction or improve controllability, for systems where conditions allows introduction of new components to a system
		1-1-6		Using maximum action and removing excess
		1-1-7		Redirecting action to a new substance
		1-1-8		Providing opposite effects by the same interaction. Subclass 1-1-8 has 2 subgroups 1-1-8-1 – 1-1-8-2
	1-2		Elimination of harmful links	
		1-2-1 – 1-2-2		Eliminating harmful interaction between two substances where a direct contact of two substances is not necessary
		1-2-3		Eliminating harmful interaction between substance and a field drawing off the negative effect
		1-2-4		Eliminating harmful or excessive interaction between two substances where direct contact between two substances must be maintained
		1-2-5		Eliminating harmful interaction between substance and a field using physical effects
2			Evolution of Su–Field (23 standards)	
	2-1	2-1-1 – 2-1-2	Complex Su–Field	Improving effect of insufficient interaction or improve controllability, for systems where conditions do not allow introduction of new components to a system
	2-2	2-2-1 – 2-2-6	Evolution of Su–Field	Improving effect of insufficient interaction or improve controllability, for systems where effect cannot be achieved by introduction of new components
	2-3	2-3-1 – 2-3-3	Evolution by coordination	Coordinating rhythms for improving effect of insufficient interaction or improve controllability, for systems where effect cannot be achieved by introduction of new components
	2-4	2-4-1 – 2-4-12	Evolution by transition to ferromagnetic and electric Su–Field	Evolving product/system using properties of ferromagnetic substances
3			Transitions to macro-level (supersystem) and transitions to micro-level (6 standards)	
	3-1	3-1-1 – 3-1-5	Transition to macro-level	Evolving product/system using transition to supersystem
	3-2	3-2-1	Transition to micro-level	Evolving product/system using transition to micro-level
4			Measurement and detection (17 standards)	Providing measurement/detection
	4-1	4-1-1 – 4-1-3	Change instead of measurement/detection	
	4-2	4-2-1 – 4-2-4	Building measurement Su–Field	
	4-3	4-3-1 – 4-3-3	Improvement of measurement systems	
	4-4	4-4-1 – 4-4-5	Transition to Field–Substance–fields for measurements and detection	
	4-5	4-5-1 – 4-5-2	Evolution of measurement systems	

5			Helpers (17 standards)	Strategies for simplification and improvement of Su–Field analyses
	5-1		Introduction of substances	
		5-1-2 – 5-1-4		Subclass 5-1-1 has 9 subgroups 5-1-1-1 – 5-1-1-9
	5-2	5-2-1 – 5-2-3	Introduction of fields	
	5-3	5-3-1 – 5-3-5	Use of phase transitions	
	5-4	5-4-1 – 5-4-2	Use of physical effects	
	5-5	5-5-1 – 5-5-3	Obtaining substance particles	

The individual types of relationships listed in the table can map the following actions:

- useful (positive) – result of interaction satisfies the users;
- harmful (negative) – the interaction results are not desired and must be eliminated;
- insufficient – a result of the interaction is positive but must be amplified;
- excessive – interaction is useful but more resources than needed are used;
- poorly controlled – interaction does not give an accurate result and/or an exact process execution.

Standard inventive solutions are divided into five main classes, which are divided into smaller subclasses of first and second order. In addition, and in some cases, subclasses are divided into several subgroups. The aforementioned standards enable various types of problems to be solved through the simple transformations of Su-Field models.

3. ANALYSIS

The subject of this analysis was the diesel engine fuel injector. It is an object that has been designed to feed the fuel at the correct pressure into the combustion chamber and to spray it properly. The cross-section of the analyzed object and the critical components are shown in Figure 3. The main components of the system are (Chybowski at al., 2017b): 1 – retaining nut, 2 – nozzle body, 3 – needle valve, 4 – nozzle cap nut, 5 – intermediate spindle, 6 – spring, 7 – O-ring, 8 – dowel pin, 9 – adjusting nut and washer, 10 – injector body.

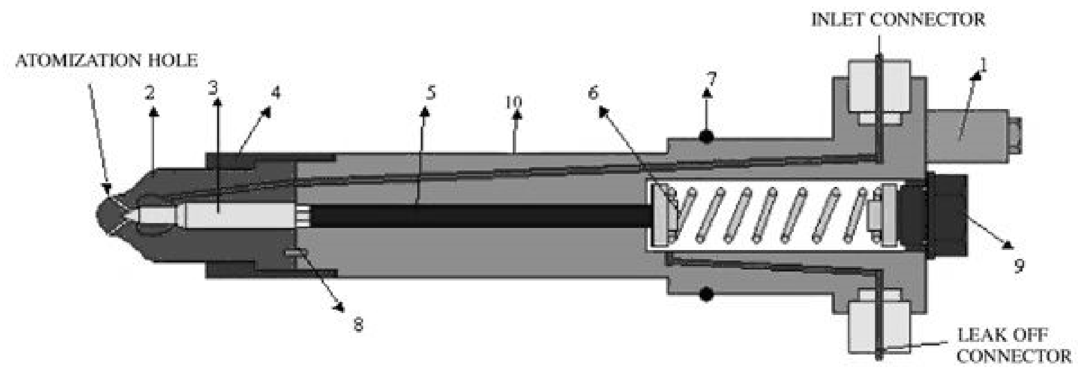

Fig. 3. Object of the analysis and its components

Source: (Marine study, 2017).

For the purposes of this analysis, the most important components of the supersystem were identified: engine block, high-pressure pipe / inlet connector, drain pipe / leak off connector, combustion chamber, fuel oil and the operator / maintenance engineer. For the system that was analyzed, a functional model of the system and a comparative matrix of problems were developed, which were detailed in (Chybowski et al., 2017b). Based on the analysis, two main problems presented in Figure 4 were identified.

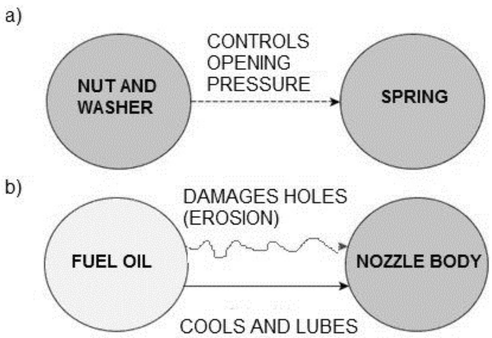

Fig. 4. Visualization of problems selected to improve the injector; a) insufficient interaction, b) negative (harmful) interaction

With reference to the first case of the example of an insufficient interaction, presented in Figure 4a, the situation concerned a problem occurring after a period of approximately 2000 hours of engine (injector) operation, when after this time the spring began to lose tension. Energization of the spring should be controlled during engine operation. For the presented situation, the Su-Field model shown in Figure 5 was built.

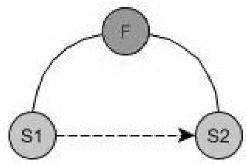

Fig. 5. Insufficient injector spring tightening model; S1 – adjustment nut and washer; S2 – spring; F – mechanical field (contact and spring force)

Figure 4b has shown the second of the analyzed problems, namely a negative (harmful) interaction. This relation is connected to the fact that fuel cools down and lubricates parts of the injector, including the nozzle body which is good, but nevertheless during the injection of the fuel oil the atomization holes suffer wear due to erosion. As a result of the problem analysis, the question arises about other ways to inject the fuel oil to reduce the wear of the nozzle body. For the presented situation, the Su-Field model shown in Figure 6 was built.

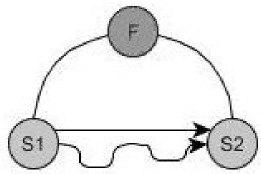

Fig. 6. The model of excessive wear to the nozzle body; S1 – fuel oil, S2 – nozzle body, F – mechanical field (contact and erosion)

For the models presented in Figures 5 and 6, the inventive standards that were applied were adequate for the type of relations and specific applications that appeared in the models mentioned in Table 4.

4. RESULTS AND DISCUSSION

4.1. Insufficient interaction

In order to find solutions to the problem of "insufficient tightening of the spring injector", selected inventive standards of Classes-1 and 2 were applied, for which the transformations of the Su-Field models are presented in Figures 7 and 8, respectively.

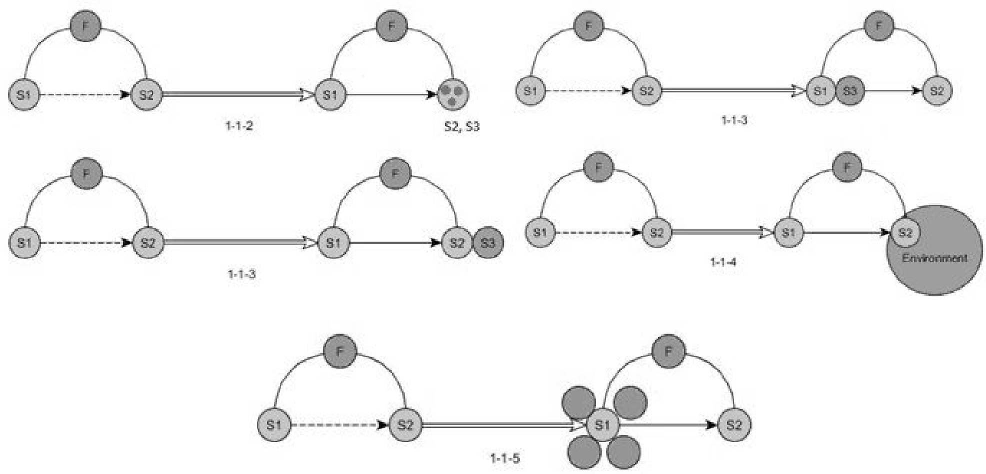

Fig. 7. Transformations of the Su-Field model for insufficient spring tension of the injector with the use of inventive standards of Class-1; S1 – adjustment nut and washer; S2 – spring; F – mechanical field (contact and spring force); S3 – additional substance

For Class-1 standards, the relevant modelled situations may correspond to the following (the list of solutions is open) actions that affect the problem:

- standard 1-1-2 – application of composite spring: internal steel core (S2) with an external polymer coating (S3);
- standard 1-1-3 (S1, S3 to S2 transformation) – application of an additional substance S3 (pushing sleeve);
- standard 1-1-3 (S1 to S2, S3 transformation) – using an additional substance S3, e.g. pressing element or additional self-tightening locking nut or thread adhesive gel;
- standard 1-1-4 – lowering the temperature of the upper part of the injector will reduce elongation of components;
- standard 1-1-5 – application of high density adhesive foam to the top of the injector spring.

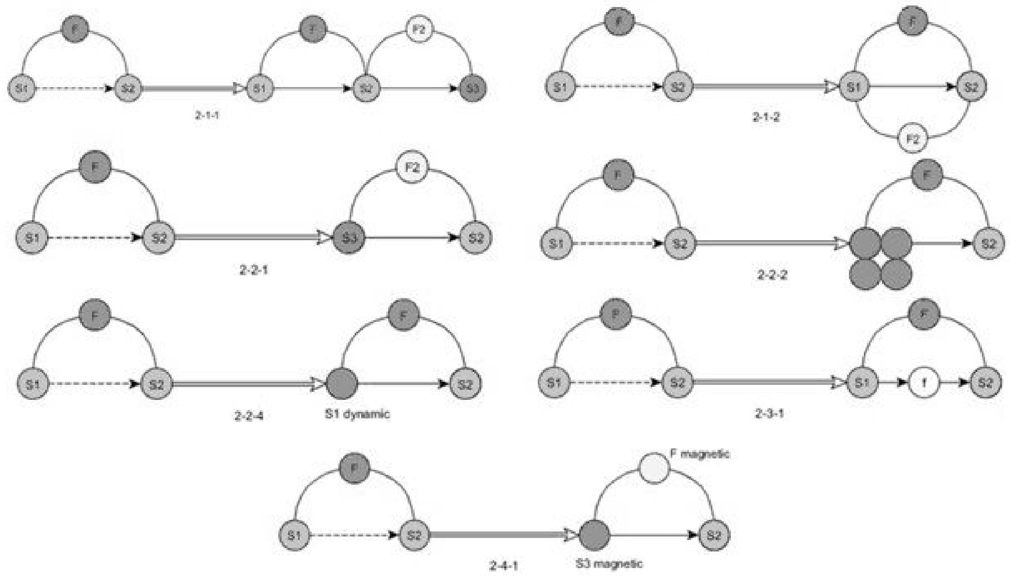

Fig. 8. Transformations of the Su-Field model for insufficient spring tension of the injector with the use of Class-2 inventive standards; S1 – adjustment nut and washer; S2 – spring; F – mechanical field (contact and spring force); F2 – additional force, S3 – additional substance, f – resonator

In the case of Class-2 standards, the relevant modelled situations may correspond to the following (the list of solutions is open) activities that have an impact on the problem:

- standard 2-1-1 – application of an additional substance and field: S3 – tensioning component, F2 – mechanical force;
- standard 2-1-2 – application of a dual Su-Field, where F2 – additional tensioning force by means of a thermal field [compensation of forces, cf. Chy18b];
- standard 2-2-1 – modification of the substance and field: S3 – solenoid, F2 – electromagnetic force;
- standard 2-2-2 – application of a nut with locking grooves or locking threads on the nut or an abrasive coating for the threads on the nut;
- standard 2-2-4 – application of a nut with an internal spring and tensioner;
- standard 2-3-1 – application of the proper natural frequency of vibration of the spring based on the estimated engine operation speed;
- standard 2-4-1 – application of the “magnetic element” (solenoid) to tension the spring and limit its position.

4.2. Negative (harmful) interaction

In order to find solutions to the problem of "insufficient tightening of the spring injector", selected inventive standards from Classes-1 and 2 were applied, for which the transformations of Su-Field models are presented in Figures 9 and 10, respectively.

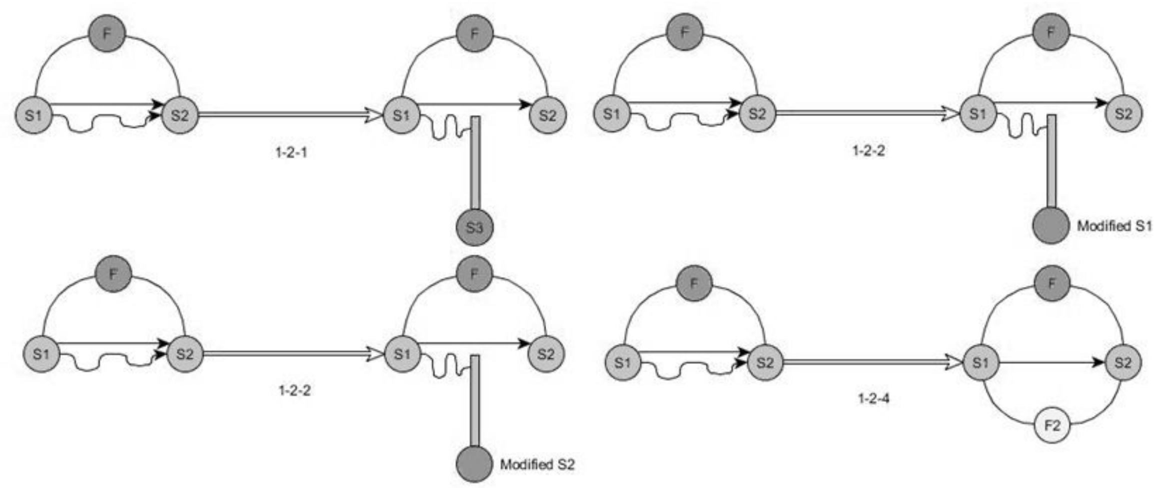

Fig. 9. Transformations of the Su-Field model for the use of erosion of the nozzle body with the use of inventive standards of Class-1; S1 – fuel oil, S2 – nozzle body, S3 – additional substance, F – mechanical field (contact and erosion), F2 – thermal field

For Class-1 standards, the relevant modelled situations may correspond to the following (the list of solutions is open) actions that affect the problem:

- standard 1-2-1 – application of an additional substance S3, e.g. protective pipes inside the atomization holes;
- standard 1-2-2 – modification of the fuel oil, e.g. application of chemical additives to the fuel oil and/or increasing the purity of the fuel (improved purification and clarification of the fuel);
- standard 1-2-2 – modification of the nozzle body, e.g. hardened internal surfaces of the atomization holes in the nozzle body;
- standard 1-2-4 – application of the dual Su-Field, e.g. additional thermal field for modifying the flow of the fuel.

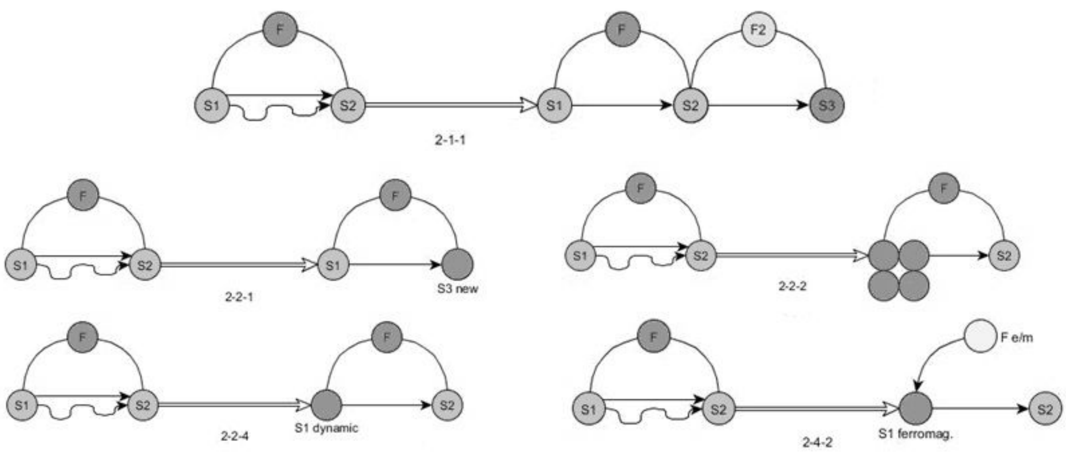

Fig. 10. Transformations of the Su-Field model for the use of erosion of the nozzle body with the use of inventive standards of Class-2; S1 – fuel oil, S2 – nozzle body, S3 – additional substance, F – mechanical field (contact and erosion), F2 – additional field

In the case of the Class-2 standards, the relevant modelled situations may correspond to the following (the list of solutions is open) activities that have an impact on the problem:

- Standard 2-1-1 – application of the chain Su-Field – F2 – mechanical field, S3 – whirl modifier for the fuel stream which will change the flow direction;
- Standard 2-2-1 – modification of the nozzle body by exchanging S2 and S3, e.g. a new generation of the nozzle body with modified hole shapes/profiles or hardened internal surfaces;
- standard 2-2-2 – S1 separation, e.g. fuel distributed in a few separate doses;
- standard 2-2-4 – modification S1, e.g. application of chemically modified fuel and/or modifying the fuel injection timing phases;
- standard 2-4-2 – application of ferromagnetic ions as an additive for the fuel as well as using an electromagnetic field to maintain these ions as a protective layer between the fuel oil and the nozzle body.

5. CONCLUSION

The analysis of the two problems mentioned above in section 4, related to the construction and operation of fuel injectors for self-ignition internal combustion engines, has shown a wide range of potential solutions.

Retrospective allocation of parts, obtained with the use of inventive standards of solutions for the improved versions of injection valves on the market, show that some of the available solutions could be successfully developed using the methodology presented in this article. This applies in particular to the use of new materials for the coating of injector components (standards 1-1-2, 1-1-5 and 2-2-2) cf. (Bryll et al., 2017; Ranachowski et al., 2013; Piesowicz et al., 2016), preparation of the top layer of machine elements (standards 1-2-1, 1-2-2 and 2-2-1 cf. (Gawdzińska et al., 2008, 2016a, 2016b; Klyus, 2009; Zolkiewski, 2016), proper preparation of thermal and chemical fuels (standards: 1-2-2 and 2-2-4) cf. (Klyus, 2006), use of additional elements in the injector and modification of the device structure (standards: 1-1-3, 1-1-4, 2-1-1, 2-1-2, 2-2-1 and 2-2-4) cf. (Raunmiagi, 2008), the use of multi-phase injection (standards: 2-2-2 and 2-2-4) cf. (Bejger, 2005), or even the use of electric fields (Dziczkowski and Zolkiewski, 2014) to control injectors (standards: 2-2-1, 2-3-1, 2-4-1 and 2-4-2), in particular in the case of piezoelectric injectors cf. (Walkowski and Smolarz, 2009). The presented collection is of an open nature.

Comparison of the results obtained, with the solutions present on the market, shows a significant application value and potential in the presented method, which is primarily the isolation of an analysis from a specific problem and thus reduces the impact of psychological inertia on the method of solving the problem. In addition it is beneficial to use the presented methodology in assessing the development possibilities of complex technical systems (Chybowski, 2009a, 2009b, 1011; Chybowski et al., 2018), in the situation where it is necessary to use multi-aspect assessments cf. (Chybowski and Gawdzińska, 2016a, 2016b, 2017c; Wiśnicki et al., 2017).

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